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Review Article

An In-Depth Review on the Eccentric Compression Performance of Engineered Bamboo Columns

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Abstract

This review paper delves into the eccentric compression performance of engineered bamboo columns, focusing on objectives like evaluating methodologies, influential parameters, and testing techniques for eccentric compression behavior. It employs a systematic literature review adhering to PRISMA 2020 guidelines to synthesize data from various studies on material properties, design parameters, and construction methods. The findings reveal challenges in predicting failure modes under eccentric compression and the need for a unified model to assess the impact of eccentricity and slenderness ratios on performance. It introduces novel insights into the standardization and testing of engineered bamboo for structural applications. It addresses a significant gap in current research by offering a comprehensive predictive framework for eccentrically loaded, engineered bamboo columns.

Keywords: Bamboo; Columns; Slenderness Ratio; Eccentric Compression; Review.

1. Introduction

In the context of the rapid evolution of modern society, there has been a noticeable increase in the favorability of structures constructed from materials derived from sustainable materials such as crumb rubber tires [1], used facial masks [2], and bamboo [3]. The inclination toward exploring sustainable building materials arises from a growing need for an enhanced human living environment. Bamboo, among the materials under scholarly investigation, has attracted increasing attention within the research community [4–7]. The modern construction industry widely uses bamboo [8–10] due to its commendable mechanical and physical properties, comparable to conventional materials such as steel [11–12]. Moreover, bamboo's environmentally friendly characteristics fuel its increasing popularity [13, 14]. These factors collectively elevate bamboo to a leading position among sustainable construction materials, warranting its comprehensive exploration and analysis in an academic context. This combination of factors has propelled bamboo to the forefront of sustainable construction materials, making it a compelling subject for thorough exploration and analysis.

Despite their potential as a sustainable and abundant resource, bamboo culms present challenges that preclude their direct use in conventional structural applications within the built environment. The wide inherent variation in geometric properties among bamboo culms complicates the establishment of a consistent grading system suitable for structural purposes [15]. Furthermore, the mechanical properties of bamboo culms exhibit significant variations influenced by factors such as species, age, and height, necessitating a comprehensive understanding of these dynamics to enable effective utilization [16–19]. Moreover, the organic nature of bamboo culms introduces compatibility issues with

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contemporary design and construction procedures, impeding their formal integration into structural applications [7]. Engineered bamboo emerges as a viable solution to overcome these challenges, as it involves the meticulous processing and treatment of bamboo culms to yield a more uniform and predictable set of material properties. Such treatment methods encompass processes like densification, delignification, and lamination, all aimed at enhancing [20]. Notably, engineered bamboo composites garner attention due to their standardized shape and relatively low variability in material properties [21]. These composites boast mechanical properties comparable to timber, rendering them suitable for diverse structural applications, including beams [22], trusses [23], frames [24], wall panels [25], and columns [26].

A column represents a vertical structural element engineered to endure compressive loads within a building or structure. Its primary function involves the transmission of loads from the superstructure to the foundation, thereby playing a pivotal role in upholding the stability and overall integrity of the construction [27]. Engineered bamboo has found application in column construction, with ongoing research focusing on its mechanical properties, connections, and standardization. This underscores its potential to significantly contribute to developing sustainable and resilient structural systems [28].

Numerous studies have investigated the performance of engineered bamboo in column applications, particularly under axial loading conditions [29–34]. However, to the best of the author's knowledge, limited attention has been directed toward understanding the performance of eccentrically loaded, engineered bamboo columns. Several pivotal challenges and research gaps have been identified, warranting further investigation to enhance the structural application of engineered bamboo. One of the foremost challenges lies in understanding and characterizing failure modes under eccentric compression. Li et al. (2020) [32] identified three characteristic failure modes for laminated bamboo lumber columns under eccentric compression, necessitating the development of predictive models that accurately reflect these behaviors across various engineered bamboo types. However, a comprehensive predictive framework that encompasses the myriad of failure behaviors, particularly for laminated bamboo lumber and parallel bamboo strand lumber, remains elusive, highlighting a significant gap in the literature.

Moreover, the influence of the eccentricity ratio and the slenderness of columns on their performance under eccentric compression is another area that demands rigorous scrutiny. Studies, such as those conducted by Li et al. (2015) [35], have shed light on the degradation of ultimate load capacity and deformation characteristics with varying eccentricity ratios and slenderness. Despite these insights, the field lacks a unified model that can predict the impact of slenderness ratio, especially for chamfered and hollow columns, underscoring a critical research void.

The variability in material properties of bamboo, including its tensile and compression strengths, further complicates the standardization of engineered bamboo for structural applications. This variability presents a considerable challenge in achieving consistent ultimate bearing capacity and structural performance under eccentric loads. Researchers have made strides towards engineering bamboo with uniform material properties, yet the effort to establish standardized grading and testing methodologies continues to fall short. Su et al. (2022) [36] emphasize the need for more focused research efforts in this domain to enable reliable predictions of engineered bamboo's performance.

This paper embarks on a comprehensive literature review to delve into the eccentric compression behavior of engineered bamboo columns. The objectives encompass the analysis of methodologies, the synthesis of influential parameters, and the evaluation of testing techniques. The study systematically explores critical factors, including material properties, design parameters, and construction methods, with a specific focus on the impact of slenderness ratio, ultimate bearing capacity, eccentricity distance, column height, and failure modes, drawing insights from the existing literature and studies.

2. Review Methodology

A systematic literature review (SLR) was employed to comprehensively assess the eccentric compression performance of engineered bamboo, drawing upon an extensive body of literature and research. The methodology adopted in this paper aligns with the principles outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 (PRISMA 2020) guidelines [37]. PRISMA 2020 is a structured reporting framework designed to enhance the transparency and quality of systematic reviews and meta-analyses. Its comprehensive 27-item checklist provides detailed reporting recommendations for various sections of the systematic review, including the title, abstract, introduction, methods, results, discussion, and conclusion [38]. This framework represents a significant advancement in the methodologies for identifying, selecting, appraising, and synthesizing studies, thereby serving the interests of authors, editors, peer reviewers, and diverse users of reviews.

The review process employed in this study adheres to the PRISMA 2020 guidelines, as depicted in Figure 1. Initially, researchers utilized two primary research databases, Google Scholar and ScienceDirect/Scopus.com, known for their ability to discern pertinent literature. These platforms offer sophisticated Boolean syntax functions, allowing users to execute searches using AND, NOT, and OR operators. The researchers meticulously chose and inputted keywords such as "bamboo," "eccentric compression," and "slenderness ratio" into the search fields of these databases. Subsequently, the initial phase identified 132 papers from Google Scholar and 19 from ScienceDirect.

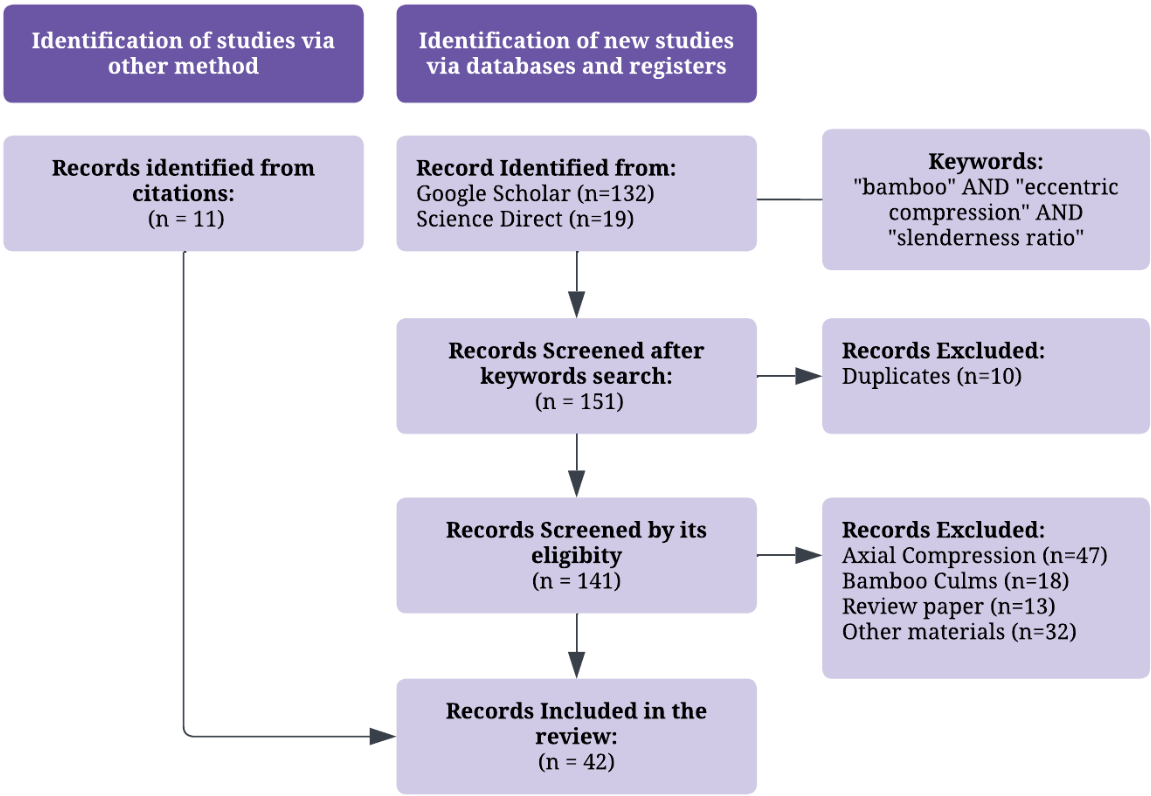


Figure 1. Review process flowchart

Following this, the identified records underwent a screening process to eliminate duplicates, extracting 10 papers. The subsequent stage involved scrutinizing the papers based on their title, abstract, content, and conclusion. The exclusion of papers followed predefined eligibility criteria: firstly, focusing on the performance of engineered bamboo in eccentric compression led to the exclusion of 47 papers concentrated solely on axial compression. Secondly, the emphasis on engineered bamboo as the primary material of interest resulted in removing 18 papers centered on bamboo culms. Thirdly, the researchers excluded all review papers and other materials, totaling 13 and 32 papers respectively. Lastly, a snowballing approach was employed, tracing relevant papers through citation trails and identifying 11 additional papers. Ultimately, a rigorous selection process yielded 42 papers that met the inclusion criteria for this comprehensive review. Upon the culmination of the review process and to achieve the main objective of this paper, the researcher is anticipated to address the following research question:

- What are the physical and mechanical properties of different engineered bamboo types used in structures?
- What are the properties of engineered bamboo columns under eccentric loads?
- What configurations define the theoretical framework and the practical test set-ups employed in assessing the eccentric compression performance of engineered bamboo columns?
- How does the eccentric compression performance of engineered bamboo columns vary, and what are the influencing factors on its outcomes?

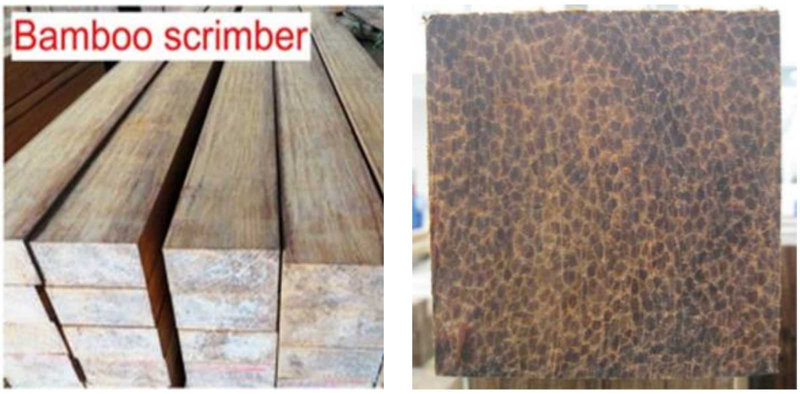
3. Engineered Bamboo

Engineered bamboo refers to bamboo-based materials that have undergone processing and manufacturing techniques to enhance their mechanical and structural properties for various applications, especially in construction and engineering. Engineering bamboo aims to make it a more reliable and versatile material with improved strength, durability, and other desirable characteristics [39]. Engineered bamboo's uniform and stable mechanical properties make it an attractive alternative to traditional construction materials such as steel, concrete, and timber [40]. Additionally, researchers have observed that engineered bamboo products exhibit outstanding physical and mechanical properties with a minimal carbon footprint, affirming their environmental sustainability.

3.1. Types of Engineered Bamboo Products

Engineered bamboo encompasses various types of composite materials developed to enhance natural bamboo's mechanical and physical properties for engineering applications. These types include (1) *Bamboo Scrimber* (B.S.); (2) *Parallel Strand Bamboo* (PSB); (3) *Laminated Bamboo Lumber* (LBL); and (4) *Glue-Laminated Bamboo* (Glubam).

Bamboo scrimber, also known as recombinant lumber, reconstructed lumber, or bamboo zephyr board, is made from small-diameter bamboo culms used to create a reconstructed structural material. The manufacturing process for bamboo scrimber initially involved truncation and splitting, softening, removal of the bamboo outer skin, defibering, drying, sizing, assembly, and hot-pressing. As technology has advanced, specific steps have been eliminated in the large-scale production of bamboo scrimber. In the current process, key stages include truncation and splitting, defibering, drying, dipping, assembly, cold-pressing, and heat curing or hot-pressing [41]. Parallel Strand Bamboo (PSB), on the other hand, is a composite material created through the high-pressure adhesive bonding of bamboo strands [42]. The initial step involves cutting bamboo culms into strips of approximately 2 meters in length, with dimensions of roughly 15 mm in width and 3 mm in thickness. These strips undergo a drying process at a temperature of around 80 °C until the moisture content decreases to below 11%. Following this step, the manufacturing process involves flattening the strips into thin strands through crushing, then saturating them with phenolic resin. Subsequently, the process aligns the strands in parallel by bonding them under elevated pressure. This technique, which orients bamboo strands parallel to the longitudinal axis and distributes them evenly in the transverse direction, effectively eliminates the raw fibers' density gradient. Consequently, the produced Parallel Strand Bamboo exhibits superior structural characteristics [43]. The difference in cross-section of these two engineered bamboos is shown in Figures 2-a, and 2-b.



(a) (b)

Figure 2. Cross-section view of (a) Bamboo Scrimber [44], and (b) Parallel Strand Bamboo Lumber [26]

The distinction between glue-laminated bamboo and laminated bamboo lumber lies in their manufacturing processes and structural properties. Glue-laminated bamboo, also known as engineered structural bamboo products (SBPs), is similar to engineered wood products such as plywood and glue-laminated timber [45]. It involves using adhesive to bond bamboo strips, allowing for large sections and spans, straight or curved, and continuous, providing excellent plastic properties for its application in structural elements [46]. On the other hand, manufacturers produce laminated bamboo lumber (LBL) using shorter and smaller strips of bamboo, butt-jointing them at sections to form longer and wider lumber or boards [47]. Figures 3-a, and 3-b show the cross-sectional views of glue-laminated and laminated bamboo lumber, respectively.

(a) (b)

Figure 3. Cross-section view of (a) Glue-Laminated Bamboo and (b) Lumber Laminated Bamboo [44]

3.2. Physical Properties of Engineered Bamboo Products

Determining the physical properties of engineered bamboo is crucial for several reasons. The design of engineered bamboo products aims to reduce the variability of natural bamboo, making understanding their physical properties essential to ensure compliance with the required standards for structural applications [48]. Engineered bamboo strives to offer a more uniform and stable material than natural bamboo, with the physical properties playing a significant role in achieving this objective [49]. The density and moisture content significantly influence the performance of engineered bamboo as a structural member. For example, bamboo scrimber, a type of engineered bamboo, can exhibit densities ranging from 980 to 1,160 kg/m³, nearly twice that of raw bamboo [50]. This increased density correlates with enhanced mechanical properties, including higher compressive strength and improved dimensional stability, making it more suitable for structural applications [20]. Moisture content's impact on the mechanical properties of bamboo is clear, as fluctuations in moisture content cause substantial dimensional changes that compromise the material's mechanical performance [51]. Additionally, the compressive strength parallel to the grain of bamboo elements decreases notably with increasing moisture content until it reaches the saturation point, highlighting the adverse effects of excessive moisture on mechanical properties [20]. Moreover, moisture content critically influences the dimensional stability of bamboo, which is essential for maintaining the structural integrity of engineered bamboo products [48].

Table 1 presents a comprehensive compilation of information concerning different types of engineered bamboo. The dataset encompasses a range of attributes, including bamboo species, geographical sources, moisture content, and density. This compilation serves as a fundamental reference, fostering a nuanced comprehension of the diverse physical properties inherent in engineered bamboo. Table 1 indicates the moisture content of various engineered bamboo types fluctuates between 5.13% and 11.9%. The control of this percentage is crucial, as it significantly impacts the mechanical properties of engineered bamboo [51]. Notably, researchers observe inconsistencies in the density values of each engineered bamboo. These variations can be attributed to several factors, including the bamboo species, the age at which harvesters collect it, and the location of the sample within bamboo culms. Consequently, further research is imperative to elucidate the factors influencing the properties of engineered bamboo.

Table 1. Comparison of Physical Properties of various Engineered Bamboo based on gathered literature

Engineered Bamboo	Bamboo Species	Source	Moisture Content (%)	Density (kg/m³)	Authors
BS	*Gigantochloa atroviolacea*	Indonesia	8.14	980	Sylvayanti et al (2023). [52]
BS	*Phyllostachys pubescens*)	China	7.00	1,215	Kumar et al. (2016). [53]
BS	*Phyllostachys pubescens*	China	7.00	1,160	Sharma et al. (2015). [54]
Glubam	*Guadua angustifolia*	Colombia	11.9	740.8	Correal et al. (2014). [55]
Glubam	*Phyllostachys pubescens*	China	7.00	880	Xiao et al. (2013). [56]
LBL	*Phyllostachys pubescens*	China	10.60	686	Chen et al. (2020). [57]
LBL	*Phyllostachys pubescens*	China	6.00	783	Kumar et al. (2016). [53]
PSB	*Dendrocalamus strictus*	India	11.00	1,030	Ahmad et al. (2011). [58]
PSB	*Phyllostachys pubescens*	China	7.22	11,515	Li et al. (2019). [59]
PSB	*Phyllostachys bambusodies*	Turkey	5.13	21,210	Çavuş et al. (2023). [60]

3.3. Mechanical Properties of Engineered Bamboo Products

The evaluation of mechanical characteristics in engineered bamboo is necessary for its effective utilization in structural engineering. Engineered bamboo variants, such as laminated composites and bamboo scrimber, have been conceptualized to present sustainable and high-performance alternatives to conventional construction materials. A comprehensive examination of the mechanical attributes of engineered bamboo proves essential in ensuring its structural soundness, load-bearing capacity, and sustained efficacy [45, 61] The mechanical traits of engineered bamboo, encompassing tensile strength, compressive strength, and modulus of elasticity, play a pivotal role in appraising its appropriateness for structural purposes. These characteristics dictate the material's ability to endure external forces like tension, compression, and bending, pivotal considerations in structural design and engineering [62, 63]. Additionally, the mechanical performance of engineered bamboo assumes critical significance in meeting the structural requisites of diverse applications, ranging from building structures and trusses to beams [49, 64].

Researchers have conducted several studies to characterize the mechanical properties of various engineered bamboo products adequately. The designation of each nomenclature is as follows: compression strength parallel to grain ($f_{c_\parallel}$), tension strength parallel to grain ($f_{t_\parallel}$), shear strength parallel to grain ($f_{v_\parallel}$), bending strength parallel to grain ($f_{b_\parallel}$), and static modulus of elasticity ($E_\parallel$). The absence of standardized testing protocols for the mechanical characteristics of engineered bamboo products in civil engineering has impeded their widespread adoption. Additionally, Sharma et al. [48] investigated the impact of processing methods on the mechanical attributes of engineered bamboo, underscoring the imperative for standardized testing approaches. Furthermore, the research conducted by Sharma & Vegte [20] underscored the potential of engineered bamboo for structural applications, emphasizing the need for standardized testing to address its mechanical properties. Hong et al. [49] also stressed the necessity of standardizing structural bamboo products and connections, signaling the importance of establishing testing methods to ensure the reliability and applicability of engineered bamboo in civil engineering. Previous researchers have employed established methods, including those based on the American Society for Testing and Materials (ASTM), Czech Technical Standards (CSN), and British Standards (B.S.), to assess the mechanical properties of engineered bamboo, as delineated in Table 2.

Table 2. Comparison of Mechanical Properties of various Engineered Bamboo based on gathered literature

Engineered Bamboo	$f_{c_\parallel}$ (MPa)	$f_{t_\parallel}$ (MPa)	$f_{v_\parallel}$ (MPa)	$f_{b_\parallel}$ (MPa)	$E_\parallel$ (MPa)	Author
BS	64.85	34.27	11.15	-	8,525	Sylvayanti et al (2023). [52]
BS	115.70	144.75	17	166.5	14,020	Kumar et al. (2016). [53]
BS	86.00	120	15	-	13,000	Sharma et al. (2015). [54]
Glubam	62.00	143.1	9.5	122.4	32,271	Correal et al. (2014). [55]
Glubam	51.00	82	7.2	99	10,400	Xiao et al. (2013). [56]
LBL	56.30	107.7	17.5	111.5	11,143	Chen et al. (2020). [57]
LBL	77.00	90	16	-	12,000	Kumar et al. (2016). [53]
PSB	65.80	-	-	58.3	11,700	Ahmad et al. (2011). [58]
PSB	66.90	-	-	-	11,515	Li et al. (2019). [59]

Researchers have conducted several studies to characterize the mechanical properties of various engineered bamboo products adequately. The designation of each nomenclature is as follows: compression strength parallel to grain ($f_{c_\parallel}$), tension strength parallel to grain ($f_{t_\parallel}$), shear strength parallel to grain ($f_{v_\parallel}$), bending strength parallel to grain ($f_{b_\parallel}$), and static modulus of elasticity ($E_\parallel$). The absence of standardized testing protocols for the mechanical characteristics of engineered bamboo products in civil engineering has impeded their widespread adoption. Additionally, Sharma et al. [48] investigated the impact of processing methods on the mechanical attributes of engineered bamboo, underscoring the imperative for standardized testing approaches. Furthermore, the research conducted by Sharma & Vegte [20] underscored the potential of engineered bamboo for structural applications, emphasizing the need for standardized testing to address its mechanical properties. Hong et al. [49] also stressed the necessity of standardizing structural bamboo products and connections, signaling the importance of establishing testing methods to ensure the reliability and applicability of engineered bamboo in civil engineering. Previous researchers have employed established methods, including those based on the American Society for Testing and Materials (ASTM), Czech Technical Standards (CSN), and British Standards (B.S.), to assess the mechanical properties of engineered bamboo, as delineated in Table 3.

Table 3. Various Standard Test Methods in determining the Mechanical Properties of Engineered Bamboo

Author	Mechanical Properties	Standard Test Method
Sylvayanti et al. (2023) [52], Correal et al. (2014) [55], Xiao et al. (2013) [56], Chen et al. (2020) [57]	Compressive, Tensile, Shear, Flexural and Modulus of Elasticity	ASTM D143 - Standard Test Methods for Small Clear Specimens of Timber
Kumar et al. (2016) [53]	Compressive Strength	CSN 49 0110 - Timber – ultimate compression strength parallel to the grain.
	Tensile Strength	CSN 49 0114 - Determination method of tensile strength perpendicular to the grain
	Flexural Strength	CSN 49 0115 - Determination method of the ultimate strength in the static bending.
	Shear Strength	CSN 49 0118 - Timber – ultimate shear strength parallel to the grain
	Modulus of Elasticity	CSN 49 0111 - Determination method of modulus in compression parallel to the grain
Sharma et al. (2015) [54]	Compressive Strength	BS 373 - Methods of testing small clear specimens of timber
	Tensile Strength	ASTM D143 - Standard Test Methods for Small Clear Specimens of Timber
	Flexural Strength	BS EN 408 - Timber structures – Structural timber and glue-laminated timber
	Shear Strength	BS 373 - Methods of testing small clear specimens of timber

Previous testing methods for assessing the eccentric compression performance of engineered bamboo exhibit several limitations, necessitating the establishment of a standardized testing protocol. These limitations encompass the inherent variability in both geometric and mechanical properties of bamboo [48] the absence of comprehensive investigations focused solely on the compression of natural bamboo culms [50] and the imperative to scrutinize the impact of parameters such as slenderness ratio, eccentric distances, and wall thicknesses on the ultimate bearing capacity of bamboo columns subjected to eccentric compression [36]. Moreover, there is a need for further exploration into the influence of eccentricity ratio on the behavior of bamboo columns under eccentric compression [35]. Furthermore, additional research is warranted to investigate the mechanical properties of bamboo under off-axis compression and the influence of length and compression directions on the behavior of bamboo specimens [65, 66]. Examining parameters such as the diameter–thickness ratio, cross-sectional area, and slenderness ratio on the axial compression behavior of original bamboo columns also merits attention [29]. Additionally, it is crucial to explore the mechanical properties of bamboo products and the effects of various processing methods on their mechanical characteristics [67].

Lastly, a comprehensive analysis of parameters such as slenderness ratio, eccentricity, and net cross-sectional area on the compression performance of bamboo composite columns is essential [68, 69]. This multifaceted exploration will provide valuable insights into the structural behavior and performance of bamboo-based materials under eccentric compression, contributing to developing more robust and reliable engineering practices in this domain.

4. Engineered Bamboo Columns Under Eccentric Load

Designers must consider several factors to ensure structural integrity and performance in designing columns. The column's response to various loading conditions, including wind, eccentricity, and buckling scenarios, requires a thorough design approach. Two primary scenarios arise from load application in columns: (1) concentric loading and (2) eccentric loading. Understanding the distinction between these loading conditions is vital for comprehending how columns respond to axial forces. A column under concentric loading experiences an axial load applied at its center or along the central axis, aligning with the column's geometric centerline. This alignment simplifies the analysis, as the load uniformly distributes across the cross-sectional area's centroid. Conversely, applying the axial load away from the centerline in an eccentrically loaded column generates a moment due to eccentricity—the horizontal distance between the load's line of action and the column's centroidal axis. Moreover, moisture content significantly influences the dimensional stability of bamboo, an essential factor in preserving the structural integrity of engineered bamboo products. The existing body of research primarily focuses on exploring the response of engineered bamboo columns to concentric loads [29, 30, 70]. Most columns experience uniaxial or even biaxial loading conditions. Consequently, there is a necessity for investigations into the performance of engineered bamboo under eccentric compression. Understanding the behavior of engineered bamboo under eccentric compression requires acquiring specific properties. Euler's critical buckling load theory, a cornerstone of structural engineering, provides a theoretical basis for determining the critical load that leads to instability and buckling in slender columns. Known as Euler's buckling theory, it assumes that the column is perfectly straight, homogeneous, and lacks initial imperfections. The critical buckling load, P_{cr}, is given in Equation 1.

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{1}$$

where P_{cr} is Euler critical buckling load, E is the modulus of elasticity, and L is the column length. This theory is widely used in structural design to assess the stability of columns and other slender structural members. It provides a fundamental understanding of the behavior of columns under compressive loads and is essential for predicting the load at which buckling, a form of structural failure, may occur [71]. Table 4 shows the properties of engineered bamboo columns from several studies identified by this paper to be subjected to evaluation of eccentric compression performance.

Table 4. Engineered Bamboo Properties under Eccentric Loadings

Engineered Bamboo	Cross-section dimension (mm)	Height (mm)	Eccentricity (mm)	Modulus of Elasticity (MPa)	Author
LBL	80 × 80	850-1,700	37	9,694	Li et al. (2019) [26]
PSB	96 × 96	570-1,900	20	11,515	Li et al. (2019) [59]
LBL	100 × 100	600-3,000	30	-	Zhou et al. (2021) [72]
LBL	100 × 100	1,100	0-120	-	Hong et al. (2021) [73]
LBL	100 × 100	1,200	0-120	8,200	Li et al. (2020) [32]
PSB	100 x 100	1,100-1,850	0-100	11,000	Huang et al. (2015) [43]
PSB	100 × 100	925-1,650	-	11,151	Wang et al. (2017) [74]
LBL	73 × 73	1,000	0-120	9,643	Li et al. (2016) [75]
LBL	100 × 100	1,200	0-120	9,694.3	Li et al. (2016) [76]
Glubam	Hollow column	1,350-1,950	40-120	11,613	Su et al. (2022) [36]
LBL	100 × 100	1,100	30-120	6,324	Jian et al. (2019) [77]
PSB	100 × 100	1,200	0-120	11,028	Li et al. (2015) [35]

Table 4 presents a comprehensive overview of studies primarily conducted in China, focusing on engineered bamboo properties under eccentric loadings. The predominant bamboo species investigated across these studies is Moso bamboo. Specifically, Laminated Bamboo Lumber (LBL) emerges as a recurrent subject in eccentric loading assessments. The modulus of elasticity, a critical mechanical property, exhibits a considerable range in the gathered literature, from 6,324 MPa to 11,613 MPa. This variability underscores the diverse mechanical behaviors observed across different studies, emphasizing the need for a nuanced understanding of the material's response under eccentric loading conditions. Exploring the independent variables employed in these studies reveals a range of methodologies aimed at comprehensively assessing engineered bamboo's eccentric compression performance. Variations in column height and eccentricity distance are prominent among the selected studies, as indicated in Table 4. Some investigations focus on altering column heights to determine the ultimate load at which the columns fail, while others manipulate eccentricity distances varying from 0 to 120 mm. These chosen parameters play a pivotal role in evaluating engineered bamboo's eccentric compression behavior, providing valuable insights into its structural performance. The subsequent section of this paper will elaborate on the theoretical and actual test setup employed in these studies, offering a more detailed exploration of the experimental methodologies applied to ascertain the material's response under eccentric loading conditions.

5. Actual Test Setup to Evaluate the Eccentric Compression Performance

In exploring engineered bamboo's eccentric compression performance, numerous considerations extend beyond the determination of physical and mechanical properties, as expounded upon in the preceding section. A crucial aspect involves delineating how the load is applied, necessitating a meticulous identification process. Engineered bamboo varieties, exemplified by Laminated Bamboo Lumber (LBL), exhibit three primary directions: (1) longitudinal, aligning parallel to the grain's length in bamboo strips; (2) tangential, running parallel to the longer side of bamboo strips; and (3) radial, oriented parallel to the shorter side of bamboo strips. This geometric arrangement is visually illustrated in Figure 4-a.

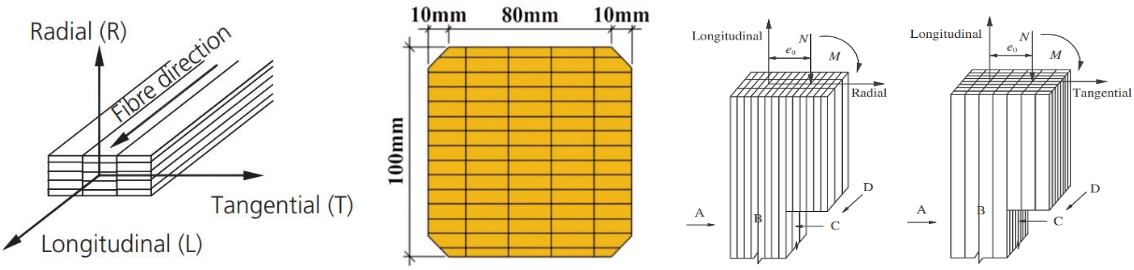


Figure 4. Visual representation of (a) three main directions of engineered bamboo [26]; (b) typical cross-section of engineered bamboo [72]; and (c) load application along radial and tangential direction [76]

For instance, Zhou et al. [72] delved into the behavior of LBL columns subjected to eccentric compression loads. Bamboo strips, measuring 7 mm × 21 mm, were intricately bonded together using resin adhesive, forming a composite of 100 mm × 100 mm, as illustrated in Figure 4-b. The researcher directed the load application along the radial axis. Analogous methodologies were subsequently adopted in studies by [75, 76]. Notably, diverse studies explored load applications in the tangential direction [72–73, 76], with Figure 4-c providing a visual representation of this specific loading orientation. Furthermore, scenarios arise where the eccentric load is simultaneously applied along both radial and tangential directions, as depicted in Figure 5, detailing the parameters of eccentricity and the skew angle as studied by Wang et al. [74]. The skew angle (β), defined as the inverse tangent of the eccentricity distance along the y-direction (e_y) over the eccentricity distance along the x-direction (e_x), is mathematically shown in Equation 2. This intricate exploration underscores the multifaceted nature of load application in assessing the eccentric compression performance of engineered bamboo, serving as a pivotal element in the comprehensive understanding of the material's structural response.

$$\beta = \tan^{-1}\frac{e_y}{e_x} \quad (2)$$

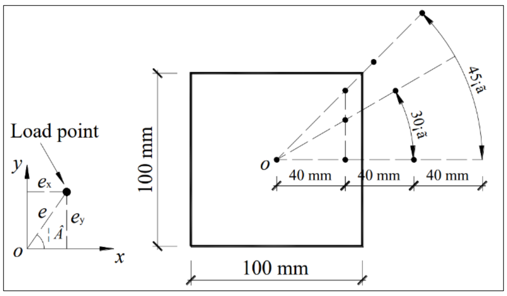
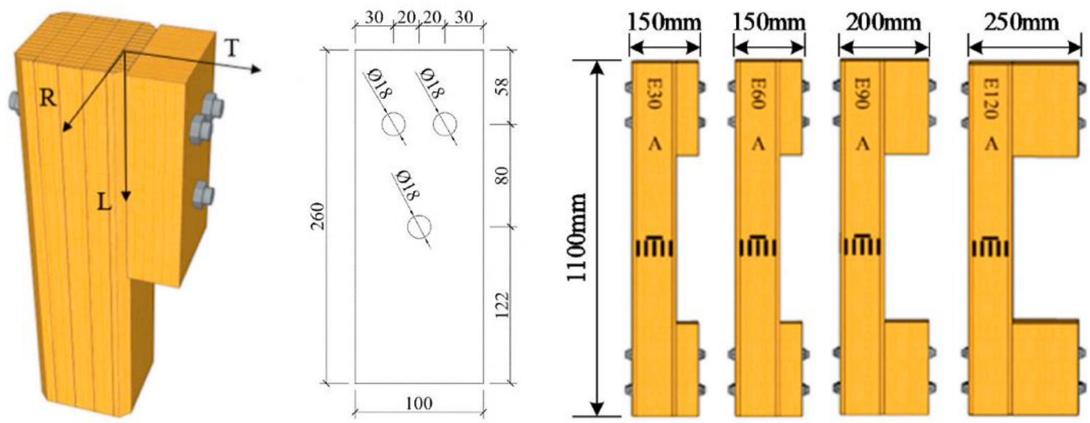


Figure 5. Load application points at the end of each engineered bamboo specimen [74]

The subsequent procedural phase involves the meticulous arrangement of the engineered bamboo under investigation, with a pivotal focus on ensuring the precise application of eccentric loads. This critical step is operationalized by affixing bamboo brackets strategically at both the upper and lower sections of the engineered bamboo, employing screw connections as shown in Figure 6-a. This methodology mirrors the approach implemented in the study conducted by Hong et al. [73], showcasing the viability and effectiveness of this setup. A comprehensive elucidation of the bamboo bracket's cross-sectional dimensions and bolt diameter is visually presented in Figure 6-b, alongside a depiction of varying eccentricity distances depicted in Figure 6-c, providing a thorough understanding of the experimental apparatus. In augmentation of this methodology, Su et al. [36] introduced an additional reinforcement layer in their study. Beyond the affixed bamboo bracket, the setup incorporates a gusset steel plate with a thickness of 10 mm. This strategic inclusion serves two purposes: it fortifies the integrity of the engineered bamboo and ensures the precision of load application, thereby minimizing the risk of inadvertent misplacement.

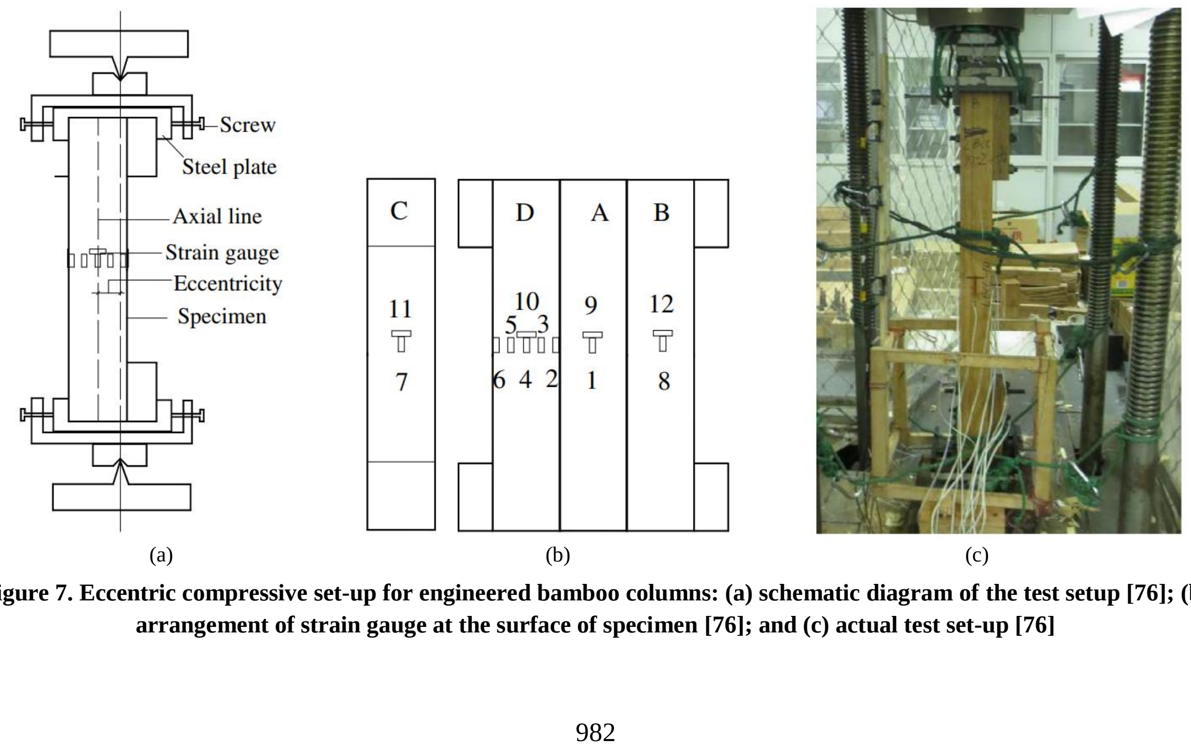


(a) (b) (c)

Figure 6. Visual representation of (a) engineered bamboo specimen with bamboo bracket screw at its end; (b) cross-sectional dimension of bamboo bracket; and (c) bamboo bracket varying distances to the specimen [73]

This augmenting gusset plate's meticulous details and dimensions are meticulously delineated in Figure 6-b, contributing to a nuanced comprehension of the sophisticated experimental configuration. These meticulously devised setups not only adhere to established protocols within the field but also underscore the paramount importance of precision and robustness in investigating eccentric compression performance in engineered bamboo.

Most studies follow the testing setup, arrangement of strain gauges, and test configurations as those demonstrated in the works of [70-77]. To prepare the engineered bamboo specimen surfaces, researchers used a rough-textured cloth to polish the surface, which they later cleaned with alcohol [75]. They applied a strain gauge to each face of the engineered bamboo, as Figure 7-b shows; a 3-laser displacement sensor was utilized to measure displacement. They then placed the bamboo on the testing machine, affixing the upper and lower ends to unidirectional hinge supports. This setup ensures the specimen can rotate freely in the eccentric direction and avoid accidental deformation outside the eccentric plane. Figures 7-a, and 7-c display the schematic diagram and the actual test setup, respectively. The comparison of actual test methods across several studies appears in Table 5. Notably, most of these studies adhere to the test standard for timber structures (GB/ T 50329–2012), adjusting the eccentricity distance of axial loads for the test setup.



(a) (b) (c)

Figure 7. Eccentric compressive set-up for engineered bamboo columns: (a) schematic diagram of the test setup [76]; (b) arrangement of strain gauge at the surface of specimen [76]; and (c) actual test set-up [76]

Table 5. Summary of the Test Set-up in Evaluating the Eccentric Compression Performance of Specimen

Engineered Bamboo	No. of Test Specimen	Displacement measuring tools	Machine	Load duration	Application of eccentric load	Authors
LBL	20	Strain gauge and Laser Displacement Sensor (LDS)	1000 kN microcomputer-controlled electro-hydraulic servo universal with TDS data acquisition system	8-12 min	Along radial direction	Li et al. (2019) [26]
PSB	27	Strain gauge and LDS		8-12 min	Along radial direction	Li et al. (2019) [59]
LBL	15	Strain gauge and LDS		6-10 min	Along tangential direction	Hong et al. (2021) [73]
PSB	24	Strain gauge and deformation sensors		2 mm/min	Biaxial load	Wang et al. (2017) [74]
LBL	35	Strain gauge and deformation sensors		8-12 min	Along radial direction	Li et al. (2016) [75]
LBL	80	Strain Gauge and LVDT		8-12 min	Both radial and tangential	Li et al. (2016) [76]

6. Eccentric Compression Performance of Engineered Bamboo

The eccentric compression performance of engineered bamboo pertains to the material's behavior under compressive loads applied away from its central axis. Several factors influence this performance, including the bamboo species, moisture content, culm age, and wall thickness. Different species exhibit variations in mechanical properties, while elevated moisture levels can reduce compressive strength. The age of the bamboo culm and the thickness of its walls also play a significant role, with younger bamboo potentially displaying different mechanical properties. Treatments, such as drying, chemical, or heat treatment, are commonly applied to enhance durability and mechanical properties. Critical considerations include joint and connection details, grain orientation, defects, and overall bamboo quality. The orientation of bamboo fibers concerning the applied load, the presence of defects, and adherence to engineering design standards also impact performance. The aforementioned factors arise from bamboo culms' inherent qualities and the manufacturing process's intricacies. However, this section of the paper focuses on exploring independent variables that impact the eccentric compression performance of engineered bamboo, drawing insights from existing literature and studies. The influential parameters, in this case, are the independent variables as follows: (1) eccentricity distance and (2) slenderness ratio. All these influential parameters will affect the dependent variables: (1) Failure modes; and (2) ultimate load-bearing capacity of engineered bamboo. This systematic investigation aims to shed light on the subtle interplay of these variables in influencing the eccentric compression behavior of engineered bamboo, thereby contributing valuable insights to the broader field of bamboo engineering.

6.1. Eccentricity Distance

The effects of eccentricity distance on the eccentric compression performance of engineered bamboo have been explored in various studies, highlighting how this factor influences the structural integrity, load-bearing capacity, and deformation characteristics of engineered bamboo columns. Table 6 provides findings from five relevant studies focusing on the type of engineered bamboo, eccentricity distance, and critical findings.

Table 6. Key Findings on the Effect of Eccentricity Distance on Engineered Bamboo based on literature

Authors	Eccentricity Distance (mm)	Engineered Bamboo	Key findings
Li et al. (2020) [32]	10-120	LBL	Increasing the eccentricity distance reduces the ultimate load-bearing capacity and an alteration in failure modes, from elastic to elastic-plastic, and finally to plastic failure as eccentricity increases.
Su et al. (2022) [36]	40-120	Glubam	The study examines the effects of slenderness ratios, eccentric distances, and wall thicknesses on GLBHC's ultimate bearing capacity, highlighting the significant impact of eccentricity distance on structural performance.
Hong et al. (2021) [73]	30-120	PBSL	Eccentricity distance impacts ultimate bearing capacity and strain distribution, decreasing as eccentricity increases. The strain distribution across the cross-section becomes more non-uniform with higher eccentricity.

The collection of studies consistently observes that the eccentricity distance affects the structural performance of various types of engineered bamboo, including Laminated Bamboo Lumber (LBL), Parallel Bamboo Strand Lumber (PBSL), Chamfered Laminated Bamboo Lumber (LBL) Columns, and Glued Laminated Bamboo Hollow Columns (GLBHC). Notably, an increase in eccentricity distance consistently reduces the ultimate load-bearing capacity and alters the failure modes of these materials. Furthermore, these effects become more pronounced with deformation characteristics and strain distribution changes across the columns' cross-section. Looking back, one can attribute the observed phenomena to the inherent mechanical properties of bamboo as a construction material and the geometric considerations of column design. The increase in eccentricity distance introduces higher bending moments and shear forces, which, in turn, exacerbate material stresses and lead to an earlier onset of failure mechanisms. This insight highlights the critical nature of eccentricity in the structural design and analysis of engineered bamboo, suggesting that minimizing eccentricity could enhance the structural integrity and performance of bamboo-based construction elements.

The underlying mechanism for the observed reduction in load-bearing capacity and alteration in failure modes with increased eccentricity can be explained through material mechanics and structural engineering principles [78-80]. As eccentricity increases, the bending moment experienced by the column increases, leading to higher stress concentrations on one side of the column [81]. This uneven stress distribution causes the material to transition from elastic behavior to elastic-plastic and eventually to plastic failure more rapidly than it would under a concentric load application [82, 83]. Additionally, the alteration in deformation characteristics and non-uniform strain distribution across the cross-section with increased eccentricity further exemplifies the sensitivity of engineered bamboo's structural performance to load application eccentricity. This sensitivity indicates the critical need to account for eccentric loading conditions in the design, analysis, and application of engineered bamboo in structural applications, ensuring safety, reliability, and optimal performance of bamboo-based construction projects.

6.2. Slenderness Ratio

Recent years have seen extensive studies on the effect of the slenderness ratio on the eccentric compression performance of engineered bamboo, with Table 7 presenting critical insights into this effect. Researchers define the slenderness ratio as the height to least lateral dimension ratio of a column, and it plays a pivotal role in determining the buckling behavior and load-bearing capacity under eccentric loading conditions.

Table 7. Key Findings on the Effect of Slenderness Ratio on Engineered Bamboo based on literature

Authors	Slenderness Ratio Range	Engineered Bamboo	Key findings
Zhou et al. (2021) [72]	21.14, 38.75, 59.89, 81.01, and 105.66	LBL	Good ductility observed in most specimens, highlighting the impact of the slenderness ratio on deformation characteristics and ultimate bearing capacity.
Hong et al. (2021) [73]	38.75	LBL	Eccentricity and slenderness ratio significantly influence ultimate bearing capacity and strain distribution.
Huang et al. (2018) [84]	45 and 57	LBL	Developed an inelastic analysis model for intermediately slender EBWC columns, highlighting how slenderness ratio affects nonlinear responses.
Chen et al. (2020) [85]	5.20, 6.93, 10.39, 11.55, 20.78, 27.71, 41.57 and 83.14	B.S.	The slenderness ratio significantly affects failure modes and load-bearing capacity, with larger ratios leading to instability failure.

Studies by Zhou et al. (2021) [72] and Hong et al. (2021) [73] have shown that with an increase in slenderness ratio, engineered bamboo columns exhibit a decrease in ultimate load-bearing capacity and a transition in failure modes from primarily compression failure in shorter columns to buckling failure in taller columns. This phenomenon is attributed to the increased propensity for lateral deflection and instability as the column's height increases relative to its cross-sectional dimensions [72, 73]. Similarly, Li et al. (2015) [35] observed that the eccentricity ratio, closely related to the slenderness ratio, significantly impacts the bearing capacity, where an increase in eccentricity leads to a reduction in the ultimate load values. This underscores the influence of slenderness on the structural efficiency of bamboo columns under eccentric loads. Furthermore, Su et al. (2022) [36] have demonstrated that the slenderness ratio affects the failure modes and the deformation characteristics of engineered bamboo columns. Columns with higher slenderness ratios showed larger lateral displacements and reduced stiffness, which significantly impacts their practical load-bearing capacity and necessitates careful consideration in design and analysis for structural applications.

In addition, the work by Huang et al. (2018) [84] on inelastic analysis models for engineered bamboo/wood composites under biaxial bending and compression has highlighted the asymmetric stress-strain relationship due to varying slenderness ratios. This asymmetry can complicate the prediction of load-bearing capacities and necessitates advanced analytical and numerical models to capture the behavior of slender columns under eccentric loading.

The observed trends can be elucidated through slender column behavior's fundamental mechanics. As the slenderness ratio of a column increases, it experiences higher susceptibility to buckling, resulting in reduced load-carrying capacity and increased deflection under compressive loads. This phenomenon is exacerbated by eccentric loading conditions, which introduce additional bending moments, further compromising the structural stability of the column. Consequently, the findings underscore the importance of considering the slenderness ratio in designing and assessing engineered bamboo structures, emphasizing the need for appropriate geometric configurations to ensure adequate structural performance and resilience against compression-induced failures.

6.3. Failure Modes

In this section of the review, three distinct studies, namely [26, 59, 72], have been identified, delving into the intricate correlation between mechanical properties and slenderness ratio. These investigations aim to elucidate the calculation of the laminated bamboo lumber's (LBL) ultimate load capacity, a pivotal determinant before structural failure occurs. The unanimous consensus among these studies underscores the recognition of two primary failure modes when subjecting engineered bamboo to axial loads. The initial mode, termed "failure mode I," manifests as the specimen initially splits around the midpoint of the columns, gradually progressing towards the inner layers as the load intensifies. Conversely, "failure mode II" is characterized by cracks exclusively appearing on the tension side of a singular main layer. These failure modes' visualizations are depicted in Figure 8 for mode I and Figure 9 for mode II. Table 8 summarizes the categorization of failure modes I and II, corresponding to different specimen heights given the variable eccentricity distance.

(a) (b) (c)

Figure 8. Failure mode I: (a) Li et al (2019) [26]; (b) Li et al. (2019) [59]; and (c) Zhou et al. (2021) [72]

(a) (b) (c)

Figure 9. Failure mode II: (a) Li et al (2019) [26]; (b) Li et al. (2019) [59]; and (c) Zhou et al. (2021) [72]

Table 8. Mode of failure and the height specimen designation

Authors	Engineered Bamboo product	Eccentricity (mm)	Specimen height (mm) and its mode of failure	
			Mode I	Mode II
Li et al. (2019) [26]	LBL	37	850, 1,100, and 1,500	1,700
Li et al. (2019) [59]	PSB	20	570, 760, 950, and 1,140	1,330, 1,520, 1,710, and 1,900
Zhou et al. (2021) [72]	LBL	30	600, and 1,100	1,700, 2,300 and 3,000

The collective findings from previous studies, as shown in Table 9, into the eccentric compression performance of engineered bamboo, specifically laminated bamboo lumber (LBL) and parallel bamboo strand lumber (PBSL), illuminate the nuanced and complex failure mechanisms inherent to these materials under load. Li et al. (2020) [32] meticulously analyzed LBL columns, unveiling three distinct failure modes: Mode I, characterized by the initiation of failure from glue or brackets with bamboo fibers remaining elastic; Mode II, where failure is precipitated by the outermost compression fiber reaching the elastic-plastic stage; and Mode III, distinguished by the outermost compression fiber achieving plastic capacity prior to failure. This study underscores the intricate interplay between material composition and failure, advocating for advanced analytical formulations to accurately predict column resistance under eccentric loads.

Table 9. Failure modes as described in other previous studies

Authors	Engineered Bamboo	Failure Modes Description
Li et al. (2020) [32]	LBL	Mode I: Failure initiates from glue or bracket while bamboo fibers remain elastic. Mode II: Outermost compression fiber reaches the elastic-plastic stage.
Li et al. (2016) [63]	LBL	Bamboo nodes and drill holes were the primary causes of failure, with mechanical properties and failure modes significantly differing based on the direction of eccentric compression.
Hong et al. (2021) [73]	LBL	Failure modes remained consistent across different eccentricities, belonging to brittle tension failure.
Li et al. (2016) [76]	LBL	Failure modes are influenced by natural defects such as bamboo joints and mechanical connectors Interaction between compression and bending in determining failure modes.

In a similar study, Li et al. (2016) [63] explored LBL column specimens subjected to radial eccentric compression, discovering failure modes significantly influenced by inherent natural defects such as bamboo joints and mechanical connectors. This research emphasizes the critical role of compression-bending interaction in determining failure, highlighting the material's variability in response to eccentric loads. Another study by Li et al. (2015) [35] on PBSL columns found that the eccentricity ratio markedly impacts bearing capacity, with an increase in eccentricity ratio correlating to a decrease in ultimate load values. This investigation offers vital insights into PBSL columns' design and application, revealing detailed failure modes across specimens.

Further contributing to the body of knowledge, Hong et al. (2021) [73] investigated the behavior of LBL columns with chamfered sections under eccentric compression. Their findings reveal that failure modes remain consistent across varying eccentricities, predominantly manifesting as brittle tension failures. This consistency across eccentricities provides a foundation for developing predictive models for LBL columns under varied load conditions. Lastly, an additional study by Li et al. (2016) [75] evaluated the mechanical performance of LBL columns under two directions of eccentric compression, identifying bamboo nodes and drill holes as primary causes of failure. This study suggests that mechanical properties and failure modes can significantly differ based on the direction of eccentric compression, introducing an essential consideration for designing and applying engineered bamboo columns.

These studies collectively enrich the understanding of engineered bamboo's mechanical behavior under eccentric compression, revealing intricate failure modes that challenge conventional design paradigms. The nuanced failure mechanisms, influenced by material composition, inherent defects, and load directionality, underscore the need for comprehensive analytical models that can accurately predict behavior and optimize the use of engineered bamboo in structural applications.

6.4. Ultimate Load Bearing Capacity

The ultimate load-bearing capacity under eccentric compression in engineered bamboo is a critical measure that directly influences the design and application of bamboo in structural engineering. Many factors affect the ultimate load-bearing capacity of engineered bamboo, which is subjected to eccentric compression as explained in the subsequent section. The convergence towards a standard theory prompts the formulation of equations by various researchers to calculate the ultimate load capacity of engineered bamboo. These equations, encapsulating the influence of mechanical properties and slenderness ratio, are succinctly presented in Table 10. Furthermore, Table 11 offers a comparative analysis, contrasting the outcomes of applying these formulas from different authors against actual test results. Key nomenclatures for equations and tables include ultimate load-bearing capacity. (N_{ult}), slenderness ratio (λ), eccentricity distance (e_o), the height of the column (h), ultimate load-bearing capacity obtained from actual test results (N_{ul}^{t}), and ultimate load-bearing capacity obtained from proposed calculations (N_{ul}^{c}).

Table 10. Comparison of Proposed ultimate load calculation based on gathered literature

Authors	Formulated ultimate load-bearing capacity	R-squared value (R^2)	Equation
Li et al. (2019) [26]	$N_{ul} = 0.029\lambda^2 - 4.72\lambda + 244.37$	0.97	(3)
Li et al. (2019) [59]	$N_{ul} = 0.0786\lambda^2 - 10.828\lambda + 493.29$	-	(4)
Zhou et al. (2021) [72]	$N_{ul} = 1.25\lambda^{\left(-0.2016\frac{e_o}{h}-0.3263\right)}\left(\frac{e_o}{h}\right)^{(0.00776\lambda-0.4069)} f_{cu}A$	0.90	(5)

Table 11. Comparison of actual test results and calculated results

Authors	Height + Eccentricity	λ	N_{ul}^t (kN)	N_{ul}^c (kN)	Error (%)
Li et al. (2019) [26]	850+37	36.8	111.1	110.7	0.4
	1100+37	47.6	82.8	84.3	1.8
	1300+37	56.3	70.7	70.8	0.1
	1500+37	65.0	63.0	61.0	-3.2
	1700+37	73.6	52.7	53.6	1.7
Li et al. (2019) [59]	570+20	20.6	293.3	310.5	5.9
	760+20	27.4	275	248.9	-9.5
	950+20	34.3	212.4	207.7	-2.2
	1140+20	41.1	185.7	178.2	-4.0
	1330+20	48	144.2	156.0	8.2
	1520+20	54.8	134.3	138.7	3.3
	1710+20	61.7	129.5	124.9	-3.6
	1900+20	68.6	99	113.6	14.7
Zhou et al. (2021) [72]	600+30	21.1	199.5	217.7	9.1
	1100+30	38.6	128.9	136.8	6.2
	1700+30	59.9	83.5	90.5	8.4
	2300+30	81.0	61.2	64.0	4.5
	3000+30	105.7	43.8	44.6	1.8

7. Gaps and Challenges

Challenges and research gaps represent fundamental concepts in the academic and scientific community. Challenges describe the obstacles or difficulties faced in a particular field of study, while research gaps indicate the areas within a specific topic or discipline lacking sufficient knowledge or understanding [86]. The eccentric compression performance of engineered bamboo, being relatively new in bamboo research, encapsulates all the necessary research gaps and challenges, as summarized in Table 12. Researchers have extensively explored the eccentric compression performance of engineered bamboo, demonstrating considerable effort. However, critical analysis uncovers a series of challenges, gaps, and limitations throughout these studies. The main research gaps and challenges in this topic include.

Table 12. Research gaps and challenges based on the gathered literature

Gaps and Challenges	Description	Authors
1. Standards and design codes	a. Lack of international standards for fully characterizing bamboo culms.	a. Li et al. (2019) [26], Hong et al. (2021) [73];
	b. Need for standardization of design codes for engineered bamboo.	b. Hong et al. (2021) [73].
2. Material characterization and other influencing factors	a. Limited number of studies on eccentric compression performance of engineered bamboo.	a. Li et al. (2019) [26];
	b. Short length of bamboo specimens with scattered strain values.	b. Li et al. (2019) [59];
	c. Lack of comprehensive studies on the mechanical performance of engineered bamboo under different loading conditions.	c. Li et al. (2016) [76];
	d. A lack of comparative analysis of the result to traditional building materials such as wood, concrete, and steel.	d. Hong et al. (2021) [73], Wang et al. (2017) [74], Li et al. (2016) [76], Jian et al. (2023) [77];
	e. Study other influencing factors to be incorporated in the proposed calculations.	e. Li et al. (2019) [26], Li et al. (2019) [59], Zhou et al. (2021) [72], Hong et al. (2021) [73], Li et al. (2016) [75].

3. Ultimate state behavior and failure analysis	a. Need for understanding the ultimate state of engineered bamboo. b. Limited investigation into failure mechanism.	a. Chen et al. (2021) [44], Wang et al. (2017) [74]; b. Chen et al. (2021) [44].
4. Models	a. Needs for better analytical and theoretical models.	Su et al. (2022) [36], Wang et al. (2017) [74], Jian et al. (2023) [77].
5. Bonding and Manufacturing	a. Further investigation needed on the bonding between bamboo strips. b. Inadequate consideration of the manufacturing process.	a. Li et al. (2016) [76]; b. Hong et al. (2021) [73].
6. Cost and Durability Analysis	a. Needs to study the cost analysis of engineered bamboo in building applications. b. Lack of consideration for long-term performance and durability.	a. Jian et al. (2023) [77]; b. Li et al. (2020) [32], Zhou et al. (2021) [72], Hong et al. (2021) [73], Wang et al. (2017) [74], Li et al. (2016) [75], Li et al. (2016) [76], Jian et al. (2023) [77], Li et al. (2015) [35].
7. Structural Exploration	a. Limited exploration of composite structure. b. Variability in lamination techniques and adhesive types.	a. Hong et al. (2021) [73]; b. Li et al. (2019) [26], Li et al. (2020) [32], Li et al. (2019) [59], Zhou et al. (2021) [72].
8. Slenderness Ratio	a. Insufficient exploration of slenderness ratio range. b. Neglect of interaction between slenderness ratio and other factors.	a. Li et al. (2019) [26], Li et al. (2019) [59], Zhou et al. (2021) [72]; b. Li et al. (2019) [26], Li et al. (2019) [59], Zhou et al. (2021) [72].

- ***Inadequate Comparative Analyses and Lack of Standardization:*** The studies by Li et al. (2019) [59], Zhou et al. (2021) [72], and the experimental and numerical study on laminated bamboo columns emphasize the insufficient comparison with other building materials and the absence of standardized practices or design codes for bamboo structures. Addressing these issues would contribute to a more comprehensive understanding of the unique properties of engineered bamboo and facilitate its widespread adoption in construction.

- ***Limited Scope of Research and Need for Long-Term Studies:*** The experimental and numerical study on laminated bamboo columns Li et al. (2020) [32], and Li et al. (2016) [76] underscored the limited scope of research, advocating for investigations beyond mechanical properties. These studies also emphasized the importance of long-term studies to assess the environmental impact, fire resistance, and durability of engineered bamboo, providing a more holistic understanding of its performance over time.

- ***Insufficient Consideration of Manufacturing Processes and Economic Feasibility:*** Li et al. (2019) [59], Zhou et al. (2021) [72], and Li and Su (2020) [32] identified gaps related to the lack of in-depth analysis of manufacturing processes and insufficient discussions on the economic feasibility and scalability of using bamboo in construction. A thorough exploration of manufacturing technology, cost-effectiveness, and energy consumption is essential for sustainable bamboo applications in construction.

- ***Failure to Address Environmental Impact and Sustainability:*** Li et al. (2019) [59], and Li et al (2016) [75] highlighted the need for a more extensive discussion on the environmental impact, sustainability aspects, and life cycle assessment of engineered bamboo. Evaluating bamboo's ecological footprint and considering its long-term behavior in real-world applications are crucial for ensuring its sustainability and promoting environmentally friendly construction practices.

- ***Challenges in Model Development and Standardization:*** Huang et al. (2015) [43], Wang et al. (2017) [74], and Su et al. (2022) [36] underscored challenges related to model development, including considerations of material nonlinearities, equilibrium equations, and ultimate loading-carry capacity. Additionally, Su et al. (2022) [36] emphasizes the need for addressing the changeable bamboo properties and discussing challenges encountered during the research process. These studies collectively call for improved models and standardized approaches in bamboo structural analysis.

- ***Neglect of Comparative Analysis and Environmental Impact Assessment:*** Li et al. (2016) [76] and Jian et al. (2023) [77] identified common gaps related to the neglect of comprehensive comparative analyses with other materials and the absence of thorough environmental impact assessments. These studies stress the importance of evaluating different reinforcement materials, conducting long-term performance analyses, and considering the environmental implications of reinforcement methods.

8. Conclusions

This review aims to identify gaps and challenges in current research on bamboo, offering a comprehensive overview of the eccentric compression behavior of engineered bamboo columns. Effectively addressing the research question, this paper aligns with the introduction by emphasizing the importance of tackling identified gaps and challenges to fully understand and utilize bamboo in construction.

Several gaps and challenges in the current research on the application of engineered bamboo as a column were highlighted, including the lack of standards and design codes, issues in material characterization, insufficient understanding of ultimate state behavior and failure analysis, outdated models, a need for further investigation into bonding and manufacturing, lack of cost and durability analysis studies, limited exploration in structural aspects, and insufficient understanding of slenderness ratio. To address these gaps and challenges, future researchers could consider exploring the following solutions:

- *Establish International Standards:* Collaborate with international organizations and researchers to develop standardized testing protocols for fully characterizing bamboo culms, providing a common foundation for evaluating eccentric compression performance.
- *Develop Comprehensive Design Codes:* Invest in research to establish design codes specifically tailored for engineered bamboo, considering material characteristics and loading conditions to provide clear guidelines for designing bamboo columns.
- *Expand Experimental Studies:* Conduct extensive experiments to investigate engineered bamboo eccentric compression performance under various loading conditions, including studies with longer specimens for a more accurate representation of real-world scenarios.
- *Incorporate Influencing Factors:* Explore and incorporate additional influencing factors into calculations and design considerations, studying the effects of environmental conditions, treatment methods, and other variables on the eccentric compression behavior of engineered bamboo columns.
- *Comprehensive Slenderness Ratio Studies:* Conduct a systematic and comprehensive exploration of the slenderness ratio range for engineered bamboo columns, testing specimens with varying ratios to understand how different proportions impact eccentric compression performance.
- *Integration of Interaction Effects:* Investigate the interaction between slenderness ratio and other relevant factors influencing the performance of engineered bamboo columns, including material properties, loading conditions, and environmental influences. Understanding these interactions will aid in developing more accurate predictive models and design guidelines.

9. Declarations

9.1. Author Contributions

Conceptualization, F.F.M.; review methodology, F.F.M. and O.G.D.; validation, O.G.D.; writing—original draft preparation, F.F.M.; writing—review and editing, F.F.M. and O.G.D.; supervision, O.G.D. All authors have read and agreed to the published version of the manuscript.

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Data sharing is not applicable to this article.

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9.5. Conflicts of Interest

The authors declare no conflict of interest.

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