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A Literature Review on Analysis and Conclusions on Steel-Bamboo Composite Material

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Abstract: This research reviews the development and evaluation of a steel-bamboo composite material. It is designed for sustainable and cost-effective construction. We chose bamboo as an affordable alternative. The study evolved into a comprehensive technical examination of bamboo's structural compatibility with steel. Bamboo has high tensile strength and low weight. Steel possesses exceptional compressive and tensile properties. This combination leads to a composite with promising mechanical performance. This hybrid material focuses on addressing challenges in modern construction. It offers strength, flexibility, and environmental benefits. This emphasis was placed on analyzing durability, corrosion resistance, thermal behavior, and long-term viability. The study also examines economic and environmental impacts. It notes reduced carbon emissions and resource consumption compared to traditional materials. Applications in rural and urban infrastructure are also taken into consideration including housing, bridges, and disaster-resistant structures. While theoretical results are promising, the paper emphasizes the need for experimental validation and performance testing under real-world conditions. The steel-bamboo composite gives a viable path toward green construction innovation, especially in developing countries seeking affordable and sustainable solutions. This research contributes to the growing interest in hybrid bio-composites and supports further exploration into their large-scale implementation.

Keywords: *Steel, Bamboo, Flexibility, Scrimber, and Corrosion Resistance.*

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I. INTRODUCTION

The use of construction materials and techniques has evolved as an answer to the environmental problems associated with buildings and structures. The carbon infrastructure resulting from construction processes like steel and concrete production has significant value in its own right and adds additional value to high carbon emissions and environmental devastation. The specific materials make use of enormous amounts of natural resources and energy, which further accelerates pollution. On the other hand, steel-bamboo composites are a new proposition as they use the recyclability of cold-formed steel and renewable strong shrubs such as bamboo scrimber, which makes them eco-friendly. It enhances the structure without causing sustainable harm to the construction's eco-friendly alternative.

Bamboo, one of the fastest-growing and most eco-friendly resources, has remarkable strength relative to its weight, making bamboo composite materials proficient. When steel is incorporated, bamboo further aids the composite by improving its mechanical properties, tensile strength, and durability. Scrimber, made from processed bamboo, is known to possess a high degree of strength and deformation resistance, which makes it suitable for different construction purposes. Further, combining bamboo with cold-formed steel composite materials boosts their performance due to being light yet strong and capable of enduring heavy loads, which in turn minimizes the usage of concrete or traditional steel reinforcements.

Nonetheless, the proper implementation of bonding procedures, load-bearing capacities, and other support frameworks greatly differentiates successful cases from others. Knowing how bamboo scrimber interacts with steel and how the material's structural properties are optimized is important to guarantee performance in reality. This study explores different methods of bonding steel and bamboo to increase the strength of the composite structure, focusing primarily on what effective bonding is capable of achieving in terms of the structure's strength and stability. Furthermore, this study examines the mechanical properties of the bamboo, particularly the compressive and tensile strength, to determine if it can serve as a principal supporting element in construction.

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For this purpose, the pat's effectiveness is augmented by subjecting the materials to several treatments such as heat, alkaline, and silane. Such processes seek to improve the mechanical properties of bamboo, improve its resilience, and contribute to its compatibility with steel. Conducting research into the effect of these treatments on bamboo's strength and performance, researchers hope to develop a specific design that maximizes bamboo's use in construction, in order to further promote its usage as a sustainable, economical reinforcement material.

Ultimately this study states the potential of steel-bamboo composites as an environmentally friendly and highly efficient material for today's construction, as by applying the latest engineering techniques and sustainable materials this research will contribute to the development of more sustainable and resilient building solutions, which can pave the way for a more sustainable future for the construction industry.

II. MECHANICAL PROPERTIES OF BAMBOO

Physical properties of bamboo vary greatly from species (species/climate type), growth patterns, soil composition, and general environmental conditions; all varieties have physical properties, e.g., density, strength, load-bearing capacity (Moisture content) These properties are greatly affected by the growing conditions in which the bamboo was grown, such as temperature, humidity, rainfall, and composting of soil. As a result, bamboo that was grown in different locations may have different physical properties, which would serve a different purpose in building, furniture making, and other sustainable purposes.

Lei et al. (2024) mentioned in the research that twelve samples of concrete composite columns were tested. The sample forms included L-shape, T-shape, and +-shape, a length of 300 mm, and the loading speed was 1 mm/min. The load-displacement curves of the sample material were studied, the failure modes were investigated, and the maximum load-bearing capacities of each column material were observed. • Lei et al. explored the interaction of bamboo scrimbers with cold-formed thin-walled steel for the analysis of their structural integrity. They reported that there was a high intermolecular interface between the materials, which ensured the efficient transfer of load. The strength characteristics and strain hardening tests showed that in all cases, the composite columns with L-shape and T-shape cross-sections had higher load-bearing capacities than those with +-shape cross-sections, and the columns with +-shape cross-sections had the highest strength capacities. This suggests that bamboo scrimber can be used as a suitable reinforcement material for steel structures for uses as sustainable and environmentally friendly construction [1]. Figure 1 Figure shows the typical stress-strain behavior of bamboo in comparison to modern material as steel.

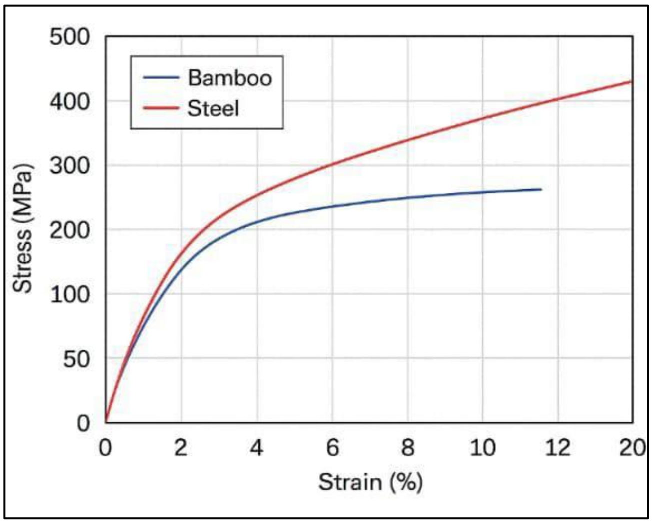

Fig 1 Stress- Strain Curves for Bamboo and Steel (Zakikhani et al., 2014)

The load-displacement behavior of steel-bamboo composite columns with different cross-sectional shapes—rectangular, T-shaped, L-shaped, and +-shaped—is depicted in Figure 1. The structural performance of each kind of bamboo geometric figure under increasing displacement is depicted in the graph. The maximum load-bearing capacity is demonstrated by L-shaped columns, which can support loads of over 200 kN, as well as T-shaped, +-shaped, and rectangular sections. Every column exhibits the usual elastic-plastic behavior, which shows material softening or structural collapse with a peak load followed by a slow fall. This information is useful for optimizing structural designs that use sustainable bamboo-based materials because it provides insight into the mechanical performance and deformation properties of various composite combinations.

Bhonde et al. (2014) carried out compressive strength tests on six bamboo specimens for mechanical investigations. A 50 mm section was cut from the central part of each bamboo specimen to obtain uniform testing conditions. The specimens were tested under controlled conditions using a standard test machine. Bhonde et al. (2014) showed that bamboo specimen exhibits an average compressive strength of 78. 03 MPa. This result emphasizes the importance of bamboo as a sustainable construction material [2].

A similar study was carried out by Sai Ram et al. (2022) comparing the compressive strength of bamboo-reinforced concrete (BRC) and plain cement concrete (PCC) for 7, 14, and 28 days. T The result showed that BRC has higher compressive strength than PCC, with mean values of:BRC: 20. 38 N/mm2 (7 days), 21 5 N/mm2 (14), and 23. 21 N/mm2 (28 days). PCC: 18. 5, 8 n/mm2 (7 days), 19. 7 n/mm2 (14) and 20. 9 n/mm2 (28 days).

This produces an increase of 10-15% in compressive strength in bamboo resulting from reinforcement. Also, Sai Ram et al. report that thinner bamboo tubes have higher compressive strength due to the high proportion of outer skin (which is better tensile resistance). They also note that lignin contributes to bamboo compressive strength, whereas cellulose increases the tensile strength and resistance to buckling.

Analysis of the data using STAAD. PRO software confirmed the presence of structural safety in a combination of bamboo and steel reinforcement with no loss of strength and therefore demonstrated that bamboo can be used as an economical and environmentally friendly alternative to steel reinforcement in construction [3].

The multi-step process that Wang et al (2021) developed to modify the mechanical properties of bamboo was developed to make bamboo steel.

- Lignin removal using Kraft pulping to improve flexibility.
- Microstructural analysis via SEM imaging to observe vascular bundles and parenchyma cells.
- Densification to enhance strength.
- Epoxy infiltration for improved durability.

Wang et al. The results of tensile tests showed that the strength of bamboo fibers decreased with length, from 1178 MPa (10 mm) to 543 MPa (50 mm), as well as that of bamboo steel, which decreased from 407.6 MPa to 309.9 MPa. The results of crack growth analysis showed controlled failures, so bamboo steel could be used for construction and engineering applications with high performance and a green nature [4].

Suryanto et al. (2022) assessed the tensile strength of six species of bamboo from Sumatra Island by ISO 22157: 2004. Bamboo specimens were cut into measured sizes and tested with a tensile testing machine. Results of tensile strength varied between species and among culm positions. Betung bamboo (bottom section) showed the highest tensile strength at 2868 kg/cm2, while Butar bamboo (middle section) showed the lowest tensile strength at 932 kg/cm2. Suryanto et al. found that the tensile strength of bamboo generally increased from bottom to top due to an increase in the number and distribution of vascular bundles.

Those results also indicate that the type of species and culm position play an important role in bamboo's tensile properties, with Betung bamboo suited to composite materials and structural applications [5]. Zhang et al. (2019) tested the tensile strength of bamboo with a Universal Testing Machine (UTM). The test involved seasoned and unseasoned bamboo samples chosen according to diameter and age (≥3 years). The samples were moisture-resistant treated and fixed in testing grips. A progressive tensile load was applied until failure, and stress was determined. Zhang and co authors reported that the tensile strength varied from 140 N/mm² to 280 N/mm², a value similar to mild steel. They verified that outer fibers contributed significantly to the strength.

The research validated that bamboo is a cost-efficient and sustainable substitute for steel reinforcement [6].

Wang et al. (2015) analyzed the bending capacity of composite structures made of bamboo and reported that incorporation of self-tapping screws and laths of bamboo greatly increased strength and stability. Experimental analysis illustrated that the ultimate bending capacity for composite slabs varied from 9.0 kN·m to 30.0 kN·m, whereas for composite beams it ranged from 12.75 kN·m to 36.13 kN·m. Wang et al. also emphasized that bamboo-steel composite beams are efficient in eliminating steel buckling problems, providing better ductility and structural integrity. The findings highlight the use of bamboo as a high-performance and sustainable material for new-age construction purposes [7].

A comparative analysis of the studies reveals many aspects. On the treatment of bamboo, we get forms like bamboo scrimber, which offers significant structural advantages across diverse applications. Lei et al. (2024) showed that bamboo scrimber, when bonded with cold-formed steel, substantially enhances the axial load-bearing capacity of composite columns. T-shaped and +-shaped columns showed the highest strength during experiments. Apart from material combination, cross-sectional geometry also plays an important role indicates that in load distribution.

On the other side, Bhonde et al. (2014) focused on untreated bamboo. He demonstrated that a bamboo possesses an average compressive strength of 78.03 MPa. This seems favourable but may not reflect the peak potential of bamboo under optimized conditions.

Sai Ram et al. (2022) took a different scenario. He integrated bamboo into concrete and formed bamboo-reinforced concrete (BRC). Their findings showed a consistent 10–15% increase in compressive strength compared to plain cement concrete (PCC)on especially over 28 days. This shows bamboo's abilities are effective in steel composites as well as enhancing cementitious materials. He observed the role of outer skin and cellulose-lignin composition. He concluded that bamboo's microstructure influences performance.

Wang et al. (2021) introduced the concept of “bamboo steel”. He has done the treatment of bamboo both physically and chemically. It demonstrated that treated bamboo can have tensile strength as much as traditional materials. This approach fills the gap between raw bamboo and traditional construction materials. He showed positive impacts of treatment that gained mechanical properties.

Overall, these studies combined focus that untreated bamboo already provides considerable structural capabilities. Its performance can be significantly enhanced through treatments and optimized geometry as well as composite configurations. The choice of bonding technique, the species and section of bamboo used, and the type of structural system (steel composite vs. concrete composite) all affect the final performance. So, future design considerations should integrate these composites to maximize bamboo's potential in sustainable

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structural applications.

III. DIFFERENT TREATMENTS ON BAMBOO

➢ *Heat* Treatment Process

Jiang et al. (2017 found that by applying heat treatment to bamboo, we can create fiber bundles. The bamboo fibers are heated at various temperatures, typically ranging from 160°C to 220°C, for durations between 30 minutes to 3 hours. The treatment is aimed at improving the mechanical properties of the fibers, particularly their tensile strength and resistance to environmental factors. Jiang and his colleagues found out that higher temperatures generally led to increased fiber brittleness, whereas lower temperatures offered better preservation of mechanical properties. The treated fibers were then tested for their structural integrity and compared with untreated fibers to analyze the improvements effected.

➢ *Alkaline Treatment*

Jiang et al. (2017) also studied alkaline treatment. It is one of the widely used chemical methods that modifies natural fibers. After that, it can be used for composite applications. In this process, we treat fibers with an alkaline solution, like sodium hydroxide (NaOH), which removes impurities such as lignin, hemicellulose, wax, and oils present on the surface of the fiber. On doing this operation, alkaline treatment improves the fiber roughness and improves mechanical interlocking with the matrix material in composites. Jiang and colleagues noted that optimized alkaline treatment improves the durability, strength, and compatibility of natural fibers in composite applications. It is a widely used technique in industries like automotive, construction, and aerospace.

➢ *Silane Treatment*

Jiang et al. (2017) also explored silane treatment. This technique is an effective chemical modification technique.

This is used to improve the bonding between natural fibers and polymer matrices in composite materials materials. This Silane coupling agent behaves as a bridge that connects the fiber surface and the polymer. It increases compatibility and adhesion. Jiang and his colleagues found that this process takes place on the hydrolysis of silane in the presence of moisture. It forms silanol groups. These silanol groups react with the hydroxyl groups thatare present on the fiber surface. This creates strong covalent bonds. As a result, the treated fibers exhibited reduced water absorption,improved durability, and improved mechanical strength. Jiang et al. concluded that silane treatment is beneficial. It gives high-performance applications where moisture resistance and mechanical strength are crucial.

➢ *The Moisture Content Test for Dendrocalamus Strictus*

The Moisture Content Test for Dendrocalamusstrictus was conducted by using the Oven Dry Method [9]. It aims to determine what amount of moisture present in bamboo samples. The process involved selecting bamboo specimens from different sections (bottom, middle, and top) and cutting them into uniform sizes.

First, the initial weight (W_i) of each sample was measured before drying. The samples were then placed in an oven at 103 ± 2°C for 24 hours or until a constant weight was achieved. After drying, the final weight (W_d) was recorded.

The results demonstrated that the lower section of the bamboo had higher moisture content. The upper section had lower moisture levels. This variation is attributed to the natural water distribution in bamboo culms.

IV. EFFECT OF MOISTURE

Effect of the moisture on the Mechanical Properties of Bamboo Water significantly influences the mechanical strength of bamboo, reducing its strength and durability. According to research, water saturation over time erodes the tensile, compressive, and fracture strengths of bamboo.Lakkad and Godbole (1986) [10] conducted experiments with dry, soaked, and boiled bamboo. After 144 hours of water exposure, tensile strength decreased by 36.9%, and compressive strength decreased by 50%. The tensile modulus of elasticity decreased by 47.7%, and it had a very significant weakening effect.

Liou et al. (2011) tested [11] fracture toughness and found that dry bamboo was 31.2 MPa√m, while wet bamboo's fracture toughness decreased by 39% to 19.1 MPa√m This suggests that dampness debilitates bamboo's resistance to cracks.

Thwe and Liao (2002) [12] studied long-term water absorption effects in bamboo-polymer composites. Tensile strength was reduced up to 13.95% after 1200 hours of immersion, while SEM analysis indicated fiber swelling, rough surface, and splitting, further lowering strength.

Therefore, exposure to moisture severely reduces the properties of bamboo. Adequate waterproofing treatments are necessary to increase durability, particularly in exterior applications.

V. PRACTICAL APPLICATIONS OF STEEL-BAMBOO COMPOSITES

Steel-bamboo composites provide a new approach in real-world construction domain. It becomes more effective, especially in those regions where sustainability, cost-efficiency, and rapid construction are more important. In rural and semi-urban areas of developing countries where traditional composites can be more costly. In those areas, it can be used to build affordable housing. These provide strength and durability. Bamboo has a lightweight nature, and when combined with cold-formed steel, it allows easy transportation. Due to its lightweight weight its assembly makes it ideal for prefabricated structures.

Moreover, in disaster-prone regions, such as earthquake or flood-affected zones, it can be a boon. Bamboo-steel composite structures can offer flexible yet strong shelters. It resists cracking and collapse, which is an

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important factor for these areas. Their ductility and energy-absorbing capacity make them suitable for temporary and permanent structures. Green building projects also benefit from such materials due to their low carbon footprint and renewable sourcing. Integrating bamboo reduces the use of cement and steel. It also promotes carbon sequestration. As a result, it contributes to environmentally responsible development. These composites can be use for use in footbridges, scaffolding, partition walls, and modular classrooms of schools. It is also beneficial in resource-limited settings. On proper treatment and bonding techniques, its lifespan and resilience can be increased. In conventional building materials, making them a viable option for mainstream architectural design and civil engineering.

VI. CONCLUSION

It is a famous choice for environmentally friendly buildings. its high strength, low weight, and rapid regrowth make it eco-friendly. Bamboo has an average crush strength of 78.03 MPa, which is comparable to some engineered woods and light concrete, according to Bhonde et al. (2014). Bamboo's strength as reinforcement was supported by Sai Ram et al. (2022), who found that BRC was 10–15% stronger under pressure than PCC. These findings demonstrate bamboo's potential for construction projects where sustainability and a high strength-to-weight ratio are crucial. However, for bamboo to be into composite structures, bonding techniques are essential. According to Bhonde et al. (2014), studies have been made on various bonding techniques, such as hybrid reinforcement strategies, mechanical fasteners, and adhesive bonding. mechanical fasteners like self-tapping screws offer extra structural stability, adhesives enhance stress distribution, and uniform load transfer. methods like epoxy infiltration have also been investigated in research. Its use and exposure to the environment influence the bonding technique selection for it to be more effectively used.

Bamboo has a lot many advantages, but its vulnerability to moisture is a drawback in construction applications. Bamboo loses half of its compressive strength due to exposure to moisture. according to Lakkad and Godbole (1986) and Liou et al. (2011) found that wet bamboo's fracture toughness decreases, suggesting a higher failure risk in moist environments. bamboo cannot be used for long-term structure building as moisture absorption causes swelling, decreased adhesion, and also causes microbial degradation, which is a major drawback for its use.

Bamboo shows a linear elastic response up to its failure point. But it lacks a yield plateau unlike steel. However, steel has high ductility and a clear yield point. bamboo shown its brittleness property. When the peak stress comes bamboo fails suddenly. Apart from this bamboo offers an impressive strength-to-weight ratio. This makes it suitable for load-bearing applications when properly applied. The sharp slope of bamboo's curve highlights its stiffness and tensile capacity. Understanding this behavior is essential when designing hybrid bamboo-steel structures for optimized performance and safety.

Jiang et al. (2017) showed that bamboo could be resistant to moisture and mechanically stable by silane coupling, alkaline soaking, and heat treatment methods. Future research should emphasize the efforts for the development of low-cost, long-lasting waterproof coatings and hybrid reinforcement techniques in order to achieve the targeted performance in bamboo. One more area for study is carrying out large-scale durability tests and using computational simulations for an in-depth understanding of the bamboo's behavior in different environmental conditions.

Whether it is about coping with moisture-related durability issues and enhancing the bonding process of bamboo, it can lead to a noticeable and sustainable construction solution for society and thus result in broader adoption of eco-friendly construction.

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