Piezo Sensor-Based Detection of Damage in Fiber-Infused Epoxy Bamboo Composites

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**Abstract.** Engineered bamboo structures have gained attention for their sustainability and mechanical properties, making them ideal for various structural applications. To enhance these properties, bamboo composites infused with epoxy and reinforced with steel and polypropylene fibers are investigated. This study explores damage identification in fiber-infused epoxy bamboo composites using piezo sensors. The electro-mechanical impedance (EMI) technique is employed to monitor and detect damage within the composite material. The experimental analysis involved subjecting the bamboo composite specimens to controlled compression loading conditions using a compression testing machine and acquiring the EMI data from the piezo sensor. Furthermore, the root mean square deviation (RMSD) method is utilized for quantitative damage assessment. Results indicate that the EMI technique effectively identifies and quantifies damage in fiber-infused epoxy bamboo composites, providing a reliable, non-destructive method for monitoring the structural integrity of engineered bamboo structures. This study underscores the potential of integrating piezo sensor technology into advanced composite materials for enhanced durability and performance.

**Keywords:** Engineered bamboo; Damage detection; EMI technique; Piezo sensors.

# Introduction

The construction industry is a major contributor to global carbon emissions, primarily due to the widespread use of energy-intensive materials such as concrete and steel [1]. As the world faces the challenges of climate change and the depletion of natural resources, there is an urgent need for sustainable building practices that minimize environmental impact while meeting the structural requirements of modern construction [2]. One promising solution is the use of renewable and eco-friendly materials, with bamboo emerging as an alternative to traditional construction materials [3]. Bamboo is a fast-growing and renewable resource, possesses remarkable mechanical properties such as high tensile strength, flexibility, and a high strength-to-weight ratio, making it a viable substitute for conventional construction materials [4]. In addition to its use in traditional construction methods, the versatility of bamboo has led to its integration into engineered bamboo structures. These structures balance mechanical strength with environmental sustainability, utilizing bamboo's natural properties to create robust, durable building components [3][5].

Recent advancements have seen the development of composite bamboo structures, which combine bamboo with other materials, such as epoxy resins and reinforcing fibers like steel and polypropylene [6][7]. These fiber-infused epoxy bamboo composites enhance the structural capabilities of bamboo, providing improved strength, stiffness, and durability.

The incorporation of reinforcing fibers significantly increases the load-bearing capacity and resistance to cracking and delamination, making these composites suitable for various structural applications, including high-dynamic loading environments [8]. Real-life applications of composite bamboo structures include their use in trusses, beams, columns, and roofing frameworks. Additionally, bamboo's natural aesthetic appeal and insulation properties make it ideal for interior and exterior wall panels, flooring, and decorative elements, offering sustainable alternatives to conventional building materials [9]. Despite the numerous advantages of bamboo and composite bamboo structures, several challenges affect their service life, particularly their durability and reliability under various loading conditions [10][11]. Bamboo composites are susceptible to environmental degradation, mechanical damage, and delamination over time, which can compromise their structural integrity [12]. Therefore, effective monitoring techniques are required to detect damage early and ensure the continued safety and performance of these materials in construction applications. The ability to monitor the health of bamboo composites non-destructively is crucial for maintaining their longevity and reducing maintenance costs, thereby enhancing their sustainability as a construction material.

To address the challenges associated with the durability and reliability of fiber-infused epoxy bamboo composites, advanced monitoring techniques such as Piezoelectric sensor-based damage detection have emerged as vital tools. Piezoelectric sensors, known for their sensitivity to mechanical vibrations and deformations, offer a promising solution for non-destructive damage detection in composite materials [13]. The electro-mechanical impedance (EMI) technique, which utilizes piezo sensors, provides a reliable approach for detecting and monitoring damage in bamboo composites. The EMI technique measures the changes in the electrical impedance of the structure, which are directly correlated with the mechanical properties of the structure. Any alterations in the structure due to cracks or damage, result in changes to the impedance signature, enabling early detection of damage [14][15][16]. This method allows for real-time monitoring of the structural integrity of fiber-infused epoxy bamboo composites without causing any harm to the material. The objective of this study is to detect the damage in fiber-reinforced composite bamboo structures using surface-bonded piezoelectric sensors. Additionally, the severity of damage evaluated using statistical indices under compression loading. By employing this technique, researchers and engineers can gain valuable insights into the performance of structure throughout their service life, identifying potential failure points before they pose a risk to structural safety.

# Materials

The preparation of bamboo composite specimens involved the use of bamboo culms as the primary materials, combined with an epoxy matrix infused with reinforcing fibers such as steel and polypropylene. The following steps outline the preparation process for both types of composite specimens, as shown in Fig. 1. First, bamboo culms were selected and cut into uniform lengths to ensure consistency in the specimens.

The bamboo culms were then prepared by smoothing the cut surfaces to eliminate any irregularities that could affect the composite’s integrity. The epoxy resin and hardener were mixed in a 1:1 ratio by weight in a clean container to achieve a uniform epoxy mixture. The mixture was mixed thoroughly using a mixing needle for fiber infusion. For the preparation of polypropylene fiber-infused bamboo composites, the required amount of polypropylene fibers was carefully added to the prepared epoxy mixture. The mixture was then mixed gently to ensure an even distribution of fibers within the epoxy matrix. Similarly, for the steel fiber-infused bamboo composites, steel fibers were added to a separate batch of the epoxy mixture, ensuring uniform distribution of the fibers throughout the resin. The bamboo culms were securely held together using plastic wrap to maintain the structure’s shape during the filling process. The epoxy-fiber mixtures were then infused into the bamboo models. For the polypropylene fiber-infused composites, the polypropylene fiber-epoxy mixture was poured into the prepared bamboo structure, ensuring the mixture filled all spaces between the bamboo culms without leaving air pockets. The same process was followed for the steel fiber-infused composites. The specimens were then allowed to cure at room temperature for 24 hours. This curing process ensured complete hardening of the epoxy resin, enhancing the mechanical properties of the composites. After curing, the plastic wrap was removed, and any excess epoxy was trimmed from the edges to obtain finished specimens ready for mechanical testing.

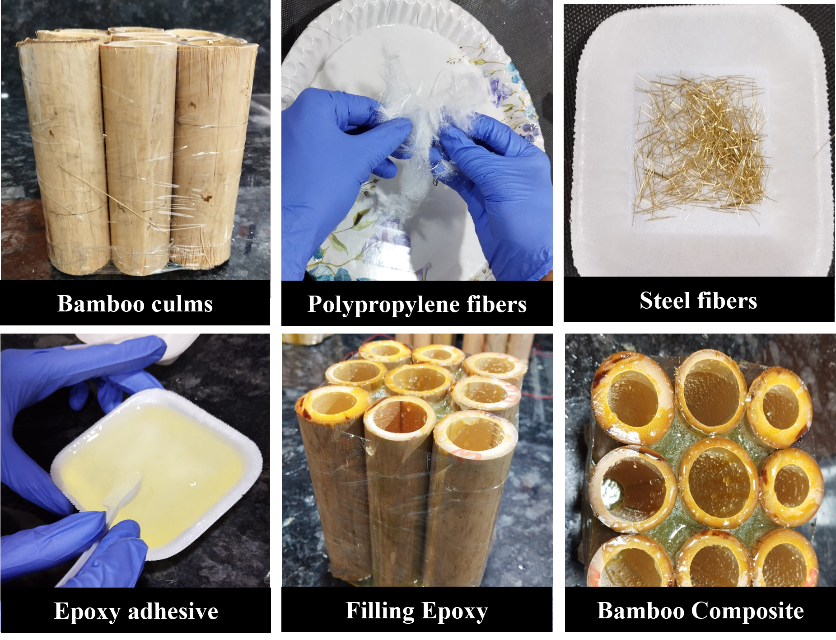


Fig. 1 Preparation of fiber-reinforced bamboo composite specimens

The installation of piezoelectric sensors on bamboo composite structures was conducted to facilitate damage detection using the EMI technique. The process starts with the preparation of bamboo composite specimens, each measuring 150 mm in height and 50 mm in diameter to ensure uniformity. Small-sized PZT patch (PI ceramic) dimensions of 5 x 5 x 0.1 mm were selected for their high sensitivity.

To prepare the bonding surface, the area on the bamboo composite was cleaned and lightly levelled to achieve a smooth and flat surface. This preparation step was critical to ensure a strong adhesive bond between the sensor and the bamboo composite. A thin layer of epoxy adhesive was then applied to the prepared surface of the composite and attached piezoelectric sensor. The piezoelectric sensor was carefully positioned onto the bamboo composite structure and held in place until the adhesive cured, ensuring proper alignment and bonding. The installation of the piezoelectric sensor on the bamboo composite surface for the EMI technique is shown in Fig. 2. The adhesive was allowed to cure for 24 hours at room temperature to ensure a robust bond between the sensor and the composite surface.

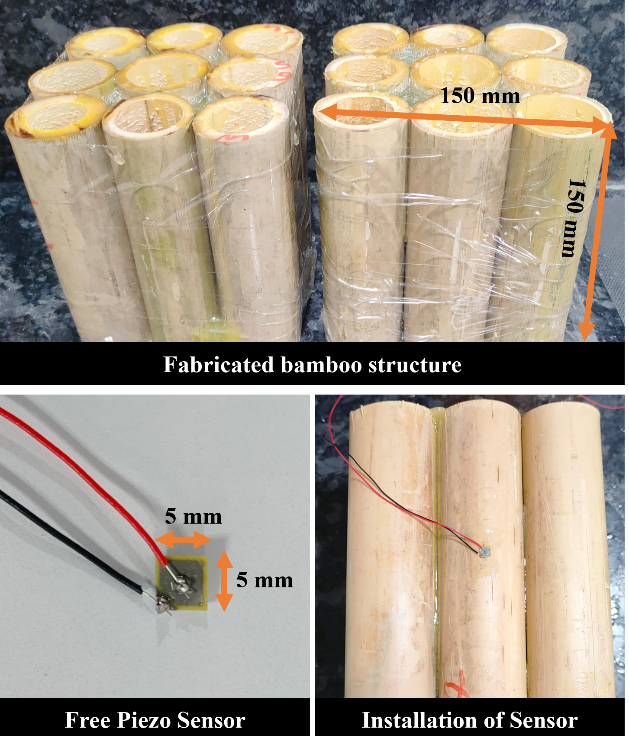


Fig. 2 Installation of the piezoelectric sensor on the bamboo composite surface

# Experimental methodology

The testing of the bamboo composite specimens, equipped with surface-bonded piezoelectric sensors, was conducted under controlled compression loading conditions using a compression testing machine with a maximum capacity of 3000 kN. The experimental setup consists of an LCR meter connected to a computer for data acquisition of the conductance signatures from the piezoelectric sensor. Before and after the application of compression loading, the conductance data were acquired from piezoelectric sensors. The acquired data were used for detecting any changes in the structural properties of the bamboo composite structure that would indicate the presence of damage. The experimental setup for compression testing of bamboo composite structures is shown in Fig. 3.

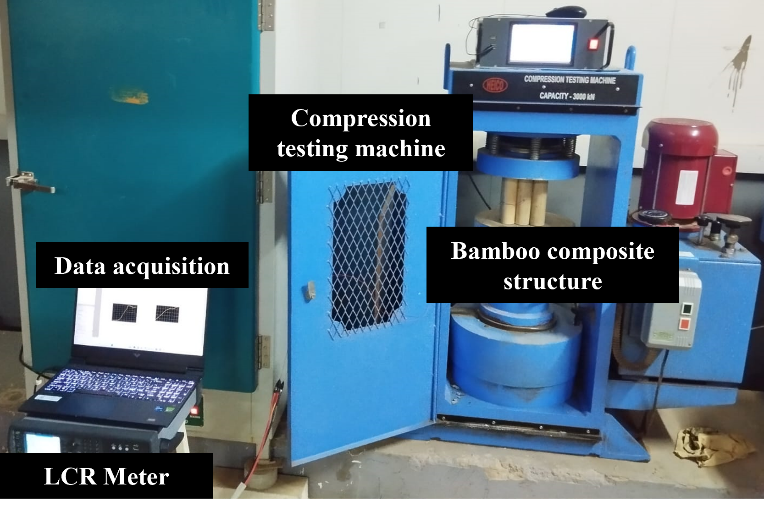


Fig. 3 Experimental setup for compression testing of bamboo composite structures

# Results and discussions

## 4.1 Damage identification using conductance signature analysis

As the load increased, the piezoelectric sensors detected changes in the conductance signature, which corresponded to mechanical changes in the composite material. The load was incrementally increased until visible signs of damage and structural failure were observed in the bamboo composite structure. Throughout this process, the piezoelectric sensors are used for continuous monitoring, allowing for the early detection of micro-cracks. After the completion of the compression tests, the conductance data was analyzed to evaluate the damage progression within the composite structures. The frequency versus conductance plots of polypropylene composite fiber in Fig. 4 show how the conductance signatures change as the applied load on the bamboo composite structures increases. Initially, the conductance signatures closely follow the baseline across the frequency range, indicating that the material's mechanical properties remain largely unchanged at lower load levels (100 to 200 kN). As the load increases to 300 kN and above, noticeable deviations from the baseline conductance signatures begin to appear. These deviations become more pronounced with further loading, particularly around 200 to 300 kHz frequency bands.

Fig. 4 Frequency versus conductance plots of polypropylene bamboo composite

A significant shift in the conductance signature is observed around the 275–325 kHz frequency range. This shift indicates the onset of microstructural changes within the composite material, such as the initiation of micro-cracks and debonding between the fibers and the epoxy matrix. At a loading of 500 kN, a further deviation in the conductance curve is observed, which is more pronounced compared to lower loads. This deviation suggests the progression of internal damage within the bamboo composite, likely due to the development of micro-cracks and fiber-matrix debonding under increasing compressive stress. At higher loads, particularly at 635 kN, the conductance signatures show substantial shifts away from the baseline. The conductance values increase sharply, indicating significant structural changes within the composite. These changes correspond to the failure modes of the composite structures, such as extensive cracking and complete failure of the fiber-reinforced sections.

Fig. 5 Frequency versus conductance plots of steel bamboo composite

Similarly, the frequency versus conductance plots for the steel fiber bamboo composite as shown in Fig. 5 demonstrate changes in conductance signatures with increasing loads. Initially, the conductance signatures are aligned with the baseline, showing no significant alterations in the composite's mechanical properties at lower load levels. However, as the compressive load increases, deviations from the baseline become more evident, particularly in the higher frequency ranges. The conductance shifts observed in the steel fiber composite plots suggest the progression of internal damage, although the rate and extent of these changes differ from those observed in the polypropylene composites. The deviations in conductance at higher loads for the steel composite indicate the presence of internal damage mechanisms, such as micro-cracking and fiber-matrix debonding, but with potentially different dynamics due to the varying reinforcement properties of steel fibers.

The EMI technique’s effectiveness in detecting damage is evident from these plots. The changes in conductance signatures directly correlate with the mechanical degradation of the bamboo composite. As the load increases, the shift in the conductance curve becomes more distinct, providing clear evidence of the progression from initial damage states to more severe damage and eventual failure.

The observed changes in the conductance signatures highlight the sensitivity of the EMI technique for early damage detection in fiber-infused epoxy bamboo composites. The incremental shifts in the curves provide a means to qualitatively assess the severity of damage at different loading stages.

## 4.2 Damage quantification using RMSD

The variation in RMSD trends between polypropylene and steel fiber composites under compression loading in Fig. 6 can be attributed to the differences in material properties and their interaction with the epoxy matrix. Polypropylene fibers, being more flexible and less stiff, tend to deform more easily under compressive stress, leading to earlier crack initiation and more rapid damage progression. This results in a higher RMSD increase, reflecting greater internal changes and damage accumulation. In contrast, steel fibers, with their higher tensile strength and stiffness, provide better support and reinforcement within the composite structure. This enhances the material's ability to withstand compressive forces, delay crack initiation, and control crack propagation, resulting in a slower increase in RMSD values. The lower RMSD at higher loads for steel composites confirms their superior damage resistance and structural performance under compression.

Fig. 6 Variation of RMSD for polypropylene and steel fiber composite bamboo structure

# Conclusion

Incorporating piezo sensor technology into the monitoring of bamboo composites not only enhances their durability and performance but also supports the principles of a circular economy. By enabling the early detection and repair of damage, this technology helps to extend the service life of bamboo structures, reduce material waste, and promote more sustainable construction practices. The study demonstrates that piezoelectric sensors, coupled with the EMI technique effectively monitor and detect damage in fiber-infused epoxy bamboo composites. The changes in conductance signatures provide a reliable indication of the onset and progression of damage under compression loading. The RMSD analysis effectively captures the differences in damage behaviour between polypropylene and steel fiber-reinforced bamboo composites under compressive loading.

The observed trends demonstrate that RMSD is a reliable indicator of internal damage progression, with variations in RMSD values directly reflecting changes in material properties and damage mechanisms. Understanding these trends is crucial for optimizing composite design and selecting appropriate reinforcement materials to enhance the durability and performance of bamboo composites in structural applications.

# References

[1] M. Ö. Arıoğlu Akan, D. G. Dhavale, and J. Sarkis, “Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain,” *J. Clean. Prod.*, vol. 167, pp. 1195–1207, 2017, doi: 10.1016/j.jclepro.2017.07.225.

[2] S. A. R. Khan, K. Zaman, and Y. Zhang, “The relationship between energy-resource depletion, climate change, health resources and the environmental Kuznets curve: Evidence from the panel of selected developed countries,” *Renew. Sustain. Energy Rev.*, vol. 62, pp. 468–477, 2016, doi: 10.1016/j.rser.2016.04.061.

[3] B. Sharma, A. Gatóo, M. Bock, and M. Ramage, “Engineered bamboo for structural applications,” *Constr. Build. Mater.*, vol. 81, pp. 66–73, 2015, doi: 10.1016/j.conbuildmat.2015.01.077.

[4] Z. Chen, R. Ma, Y. Du, and X. Wang, “State-of-the-art review on research and application of original bamboo-based composite components in structural engineering,” *Structures*, vol. 35, no. December 2021, pp. 1010–1029, 2022, doi: 10.1016/j.istruc.2021.11.059.

[5] X. Sun, M. He, and Z. Li, “Novel engineered wood and bamboo composites for structural applications: State-of-art of manufacturing technology and mechanical performance evaluation,” *Constr. Build. Mater.*, vol. 249, no. 1239, p. 118751, 2020, doi: 10.1016/j.conbuildmat.2020.118751.

[6] H. P. S. Abdul Khalil, I. U. H. Bhat, M. Jawaid, A. Zaidon, D. Hermawan, and Y. S. Hadi, “Bamboo fibre reinforced biocomposites: A review,” *Mater. Des.*, vol. 42, pp. 353–368, 2012, doi: 10.1016/j.matdes.2012.06.015.

[7] D. Liu, J. Song, D. P. Anderson, P. R. Chang, and Y. Hua, “Bamboo fiber and its reinforced composites: Structure and properties,” *Cellulose*, vol. 19, no. 5, pp. 1449–1480, 2012, doi: 10.1007/s10570-012-9741-1.

[8] Z. Al Mahmud *et al.*, “The mechanical and microstructure investigations of jute fabric epoxy reinforced with microfibers from banana and coconut,” *SPE Polym.*, no. July, pp. 1–16, 2024, doi: 10.1002/pls2.10154.

[9] A. Rajabipour, A. Javadian, M. Bazli, and M. Masia, “Interlaminar Shear Properties of Bamboo Composite for Structural Applications,” *Fibers*, vol. 10, no. 7, pp. 1–15, 2022, doi: 10.3390/fib10070059.

[10] H. Sun *et al.*, “Review on materials and structures inspired by bamboo,” *Constr. Build. Mater.*, vol. 325, no. December 2021, p. 126656, 2022, doi: 10.1016/j.conbuildmat.2022.126656.

[11] W. N. Nkeuwa, J. Zhang, K. E. Semple, M. Chen, Y. Xia, and C. Dai, “Bamboo-based composites: A review on fundamentals and processes of bamboo bonding,” *Compos. Part B Eng.*, vol. 235, no. December 2021, p. 109776, 2022, doi: 10.1016/j.compositesb.2022.109776.

[12] N. Rahman *et al.*, “Enhanced bamboo composite with protective coating for structural concrete application,” *Energy Procedia*, vol. 143, pp. 167–172, 2017, doi: 10.1016/j.egypro.2017.12.666.

[13] J. Chen, Q. Qiu, Y. Han, and D. Lau, “Piezoelectric materials for sustainable building structures: Fundamentals and applications,” *Renew. Sustain. Energy Rev.*, vol. 101, no. January 2018, pp. 14–25, 2019, doi: 10.1016/j.rser.2018.09.038.

[14] R. Gomasa, V. Talakokula, S. Kalyana, R. Jyosyula, and T. Bansal, “A review on health monitoring of concrete structures using embedded piezoelectric sensor,” *Constr. Build. Mater.*, vol. 405, no. August, p. 133179, 2023, doi: 10.1016/j.conbuildmat.2023.133179.

[15] T. Morwal, T. Bansal, A. Azam, and V. Talakokula, “Monitoring chloride-induced corrosion in metallic and reinforced/prestressed concrete structures using piezo sensors-based electro-mechanical impedance technique: A review,” *Meas. J. Int. Meas. Confed.*, vol. 218, no. February, p. 113102, 2023, doi: 10.1016/j.measurement.2023.113102.

[16] Y. Y. Lim, S. T. Smith, R. V. Padilla, and C. K. Soh, “Monitoring of concrete curing using the electromechanical impedance technique: review and path forward,” *Struct. Heal. Monit.*, vol. 20, no. 2, pp. 604–636, 2021, doi: 10.1177/1475921719893069.