RESEARCH ARTICLE OPEN ACCESS

Comprehensive Analysis of Bolted Joint Performance in Natural Fiber-Reinforced Polymer Composites: Effects of Fiber Type, Orientation, Hybridization, and Environmental Conditions

Dr.Amol Dnyaneshwarrao Sable[1]

[1] *Department of Mechanical Engineering, College JSPM S Jayawantrao Sawant College of Engineering ,Hadapsar,Pune./* Savitribai Phule Pune University, *Pune Maharashtra , India | ORCID: 0009-0007-1908-256X*

Corresponding author email: dramolsable@gmail.com

Abstract — Natural fiber-reinforced polymer (NFRP) composites are increasingly considered as sustainable alternatives to conventional synthetic composites. Their low density, renewable origin, and adequate mechanical performance make them attractive for applications in automotive, construction, and marine industries. Mechanical fastening through bolted joints is widely used for assembling composite structures because it allows easy inspection, replacement, and maintenance. However, introducing bolt holes creates stress concentrations that may lead to premature failure. This study investigates the mechanical performance of bolted joints in NFRP composites, focusing on fiber type, fiber orientation, hybridization, and environmental effects such as moisture and temperature. Failure mechanisms including bearing, net-tension, and shear-out are analyzed. Findings indicate that optimized fiber orientation, hybrid reinforcement, and controlled environmental conditions significantly improve joint strength and reliability.

Keywords: Natural fiber composites, bolted joints, mechanical properties, hybrid composites, failure modes, environmental effects.

I. INTRODUCTION

Environmental sustainability has driven significant research into renewable composite materials. Natural fiber-reinforced polymer composites are advantageous due to their lightweight, low cost, and biodegradability. Fibers such as jute, flax, hemp, kenaf, and sisal are commonly used for reinforcement due to availability and moderate mechanical performance [1], [2].

While natural fibers offer sustainability benefits, assembling composite structures remains challenging. Mechanical fastening through bolted joints is frequently used because it permits disassembly, inspection, and maintenance [5]. However, drilling holes introduces stress concentrations that may trigger localized damage. The load-carrying capacity of bolted joints depends on fiber type, fiber orientation, laminate configuration, bolt geometry, and environmental conditions [3], [6].

Hybrid composites combining natural and synthetic fibers such as glass or carbon have been explored to enhance mechanical performance and damage tolerance [3], [9]. Understanding the interplay between fiber characteristics, joint design, and environmental effects is essential for developing reliable NFRP structures. This study presents a comprehensive evaluation of bolted joint behavior considering these factors.

II. RELATED WORK

Natural fiber composites have been extensively studied for their mechanical properties. Bledzki and Gassan [1] demonstrated that cellulose-based fibers provide significant reinforcement depending on fiber length, orientation, and interfacial bonding. Pickering et al. [2] highlighted that flax and hemp fibers offer higher tensile strength and stiffness, especially when aligned with the load direction.

Mechanical behavior of bolted joints has been investigated in various studies. Pappas et al. [7] reviewed bolted joining in fiber-reinforced polymers, emphasizing stress concentration around holes and the influence of laminate configuration on failure modes. Belingardi and Cavatorta [8] identified common failure mechanisms such as bearing, net-tension, and shear-out. Hybrid composites combining natural and synthetic fibers improve impact resistance and fatigue life while retaining environmental advantages [3].

Environmental exposure significantly affects natural fiber composites. Moisture absorption can weaken the fiber-matrix interface, reducing strength and stiffness [11]. Temperature variations may alter the matrix behavior, further affecting joint performance. Despite extensive studies, the combined effects of fiber type, orientation, hybridization, and environmental conditions on bolted joint performance remain underexplored, motivating this work.

.

III. METHODOLOGY

3. Materials and Methodology

3.1 Materials

Composite laminates were fabricated using natural fibers (flax, jute, kenaf) in an epoxy resin matrix. Epoxy was chosen for its high adhesion, stiffness, and chemical stability. Hybrid laminates included glass fiber layers to enhance strength. High-strength steel bolts were used with washers and nuts for uniform stress distribution.

3.2 Fabrication

Laminates were produced by hand lay-up followed by compression molding. Fibers were aligned according to desired stacking sequences:

- Unidirectional (0°)
- Cross-ply (0°/90°)
- Angle-ply (±45°)
- Quasi-isotropic (0°/90°/±45°)

After curing, laminates were cut into specimens, and bolt holes were drilled using high-speed carbide bits to minimize delamination.

3.3 Mechanical Testing

Specimens were tested in tension using a Universal Testing Machine. Load-displacement data were recorded to determine:

- Ultimate load
- Joint stiffness
- Energy absorption
- Failure modes

3.4 Environmental Conditioning

Selected specimens were exposed to:

- Moisture (immersion in water)
- Elevated temperatures

These tests evaluated environmental effects on mechanical properties and failure behavior.

IV. RESULTS AND DISCUSSION

4.1 Effect of Fiber Type and Orientation

Specimens with fibers aligned along the load direction exhibited higher stiffness and ultimate load. Quasi-isotropic configurations distributed stresses more evenly but had lower peak strength compared to unidirectional laminates [1], [2].

4.2 Effect of Hybridization

Hybrid laminates with glass fiber layers showed improved strength and resistance to damage propagation. Hybridization enhanced bearing capacity and delayed crack initiation around the bolt holes [3], [9].

4.3 Environmental Effects

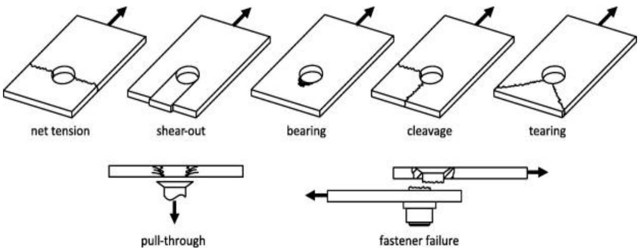
Moisture absorption reduced stiffness and ultimate load due to weakened fiber-matrix bonding. Elevated temperature softened the matrix, decreasing load-carrying capacity. Combined exposure had a cumulative negative effect on joint performance [11], [15].

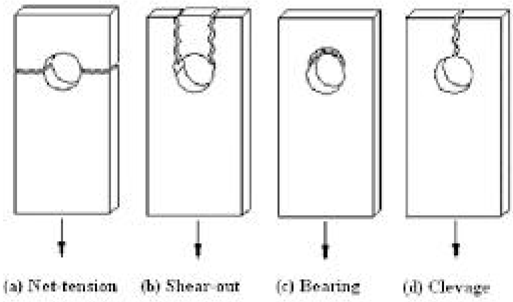
5. Failure Mode Analysis

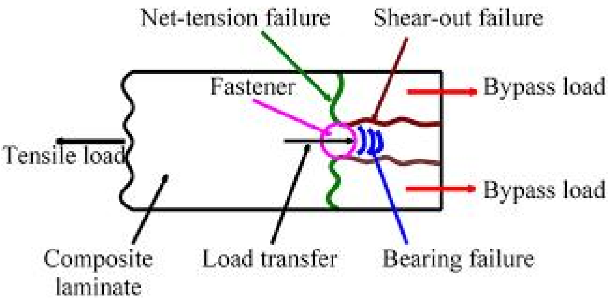
Three primary failure modes were observed:

5.1 Bearing Failure

Progressive crushing of material around the bolt hole. Considered **desirable** because damage occurs gradually [7], [8].

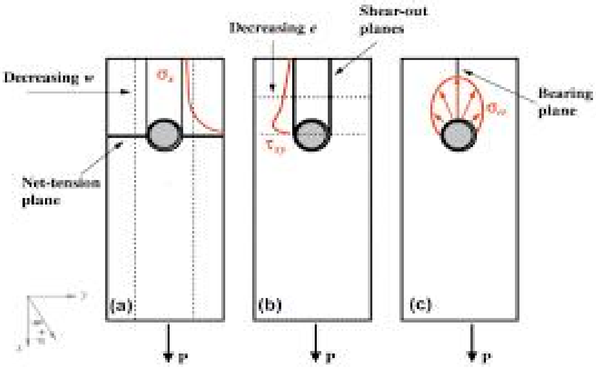


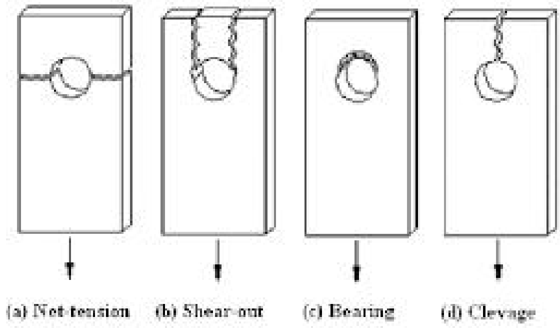


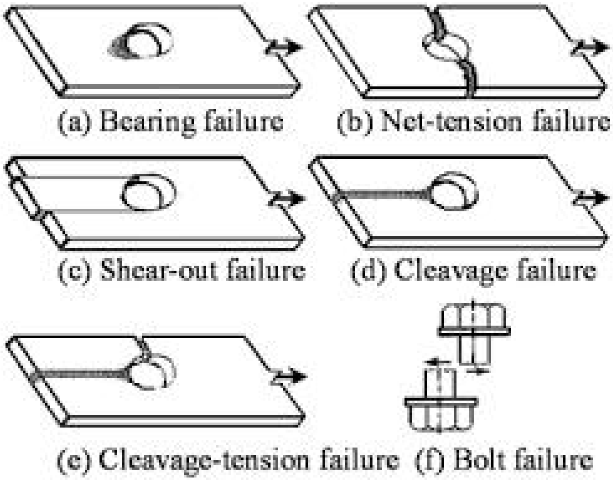


5.2 Net-Tension Failure

Sudden fracture across the width of the laminate due to tensile stress exceeding material strength. **Undesirable** [6], [14].

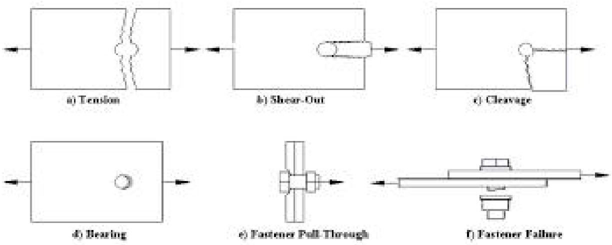






5.3 Shear-Out Failure

Failure occurs along the edge when the distance between bolt and edge is insufficient. **Undesirable** [8], [9].



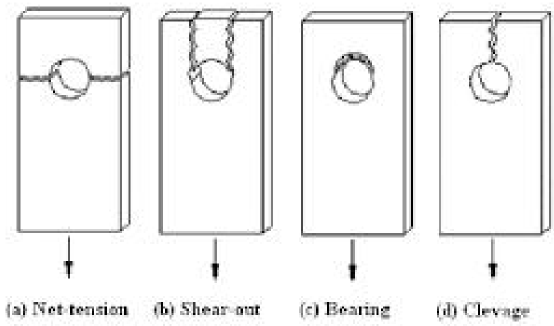


Table 1: Comparison of Failure Modes

Failure Mode	Cause	Characteristics	Design Preference
Bearing	Compression around bolt	Gradual crushing	Preferred
Net-Tension	Tensile across laminate	Sudden fracture	Undesirable
Shear-Out	Shear near edge	Tearing	Undesirable

Table 2: Factors Affecting Bolted Joint Performance

Parameter	Effect on Strength
Fiber Orientation	Controls load transfer
Fiber Type	Influences stiffness and tensile strength
Bolt Diameter	Distributes load effectively
Edge Distance	Reduces shear-out risk
Laminate Thickness	Improves joint stiffness
Environmental Exposure	Moisture and temperature reduce strength

V. CONCLUSION AND FUTURE WORK

6. Conclusion

Bolted joints in natural fiber-reinforced polymer composites are influenced by fiber type, fiber orientation, hybrid reinforcement, and environmental exposure. Key conclusions:

1. **Fiber orientation** along the load direction maximizes stiffness and load capacity.
2. **Hybrid laminates** with synthetic fibers improve bearing strength and delay crack propagation.
3. **Environmental factors** such as moisture and temperature decrease mechanical performance by weakening the fiber-matrix interface.
4. **Bearing failure** is preferred due to progressive damage, while net-tension and shear-out are undesirable.

Optimizing fiber selection, laminate design, and environmental protection is essential for reliable NFRP composite structures.

VI. DECLARATIONS

VI. DECLARATIONS

A. Funding
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

B. Conflict of Interest
The authors declare no conflict of interest.

C. Data Availability
The data that support the findings of this study are available from the corresponding author on reasonable request.

D. Ethics Statement
This study did not involve human or animal subjects.

E. Author Contributions
Conceptualization, A.D.S.; Methodology, A.D.S.; Validation, A.D.S.; Investigation, A.D.S.; Writing — original draft, A.D.S.; Writing — review and editing, A.D.S. The author has read and agreed to the published version of the manuscript.

VII. ACKNOWLEDGMENTS
The author deeply acknowledges JSPM's Jayawantrao Sawant College of Engineering, Hadapsar, Pune, for providing the necessary research facilities, laboratory infrastructure, and administrative support required to successfully execute the fabrication and mechanical testing components of this study. Special thanks are also extended to the department colleagues and laboratory assistants for their continuous technical support throughout the project.

VIII. REFERENCES

[1] A. K. Bledzki and J. Gassan, “Composites reinforced with cellulose based fibres,” *Prog. Polym. Sci.*, vol. 24, no. 2, pp. 221–274, 1999.
[2] S. J. Pickering, M. G. Aruan Efendy, and T. M. Le, “A review of recent developments in natural fibre composites and their mechanical performance,” *Compos. Part A*, vol. 83, pp. 98–112, 2016.
[3] M. Jawaid and H. P. S. Abdul Khalil, “Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review,” *Carbohydr. Polym.*, vol. 86, no. 1, pp. 1–18, 2011.
[4] R. M. Jones, *Mechanics of Composite Materials*, 2nd ed., Philadelphia, PA: Taylor & Francis, 1999.
[5] L. C. Bank, *Composites for Construction: Structural Design with FRP Materials*, Hoboken, NJ: Wiley, 2006.
[6] S. Pappas, C. T. Herath, and J. P. Davim, “Mechanical joining of fibre reinforced polymer composites to metals: Part I—Bolted joining,” *Polymers*, vol. 12, no. 10, 2020.
[7] M. Belingardi and L. Cavatorta, “Failure maps of biocomposites mechanical joints reinforced with natural fibres,” *Compos. Part C*, vol. 5, 2021.
[8] K. Yang, Y. Bai, C. Ding, and S. Y. Kong, “Comparative study on mechanical performance of bolted joints with steel and fibre reinforced polymer bolts,” *J. Build. Eng.*, vol. 41, 2021.
[9] A. Regazzi, S. Corn, P. Ienny, and A. Bergeret, “Coupled hydro-mechanical aging of flax fiber reinforced composites,” *Compos. Struct.*, 2018.
[10] Y. Zhang, X. Liu, and Q. Chen, “Failure analysis of bolted composite joints using continuum damage mechanics,” *Compos. Struct.*, 2023.
[11] J. Qureshi, “Bolted joints in fibre reinforced polymer structures,” *Res. Dev. Mater. Sci.*, 2018.