Parametric Analysis of Bolted Joint Performance in Natural Fiber Reinforced Polymer Composites

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***Abstract*: This study presents a comprehensive parametric analysis of bolted joint performance in natural fiber reinforced polymer (NFRP) composites. The influence of key parameters—including bolt diameter, edge distance, hole clearance, tightening torque, washer presence, and fiber orientation—was experimentally investigated using fabricated composite specimens subjected to tensile loading. Results revealed that joints with $[0/90]_s$ stacking sequence, tighter bolt-hole clearance, optimal torque (6 Nm), and washers exhibited improved stiffness, higher load-bearing capacity, and favorable bearing-type failure modes. Conversely, inadequate edge distance and excessive preload led to premature failures such as shear-out and fiber crushing. The findings offer valuable design recommendations for optimizing mechanical joints in NFRP composites and support their application in sustainable structural components for automotive, aerospace, and civil engineering domains.**

Keywords: Bolted joints, Natural fiber composites, Mechanical performance, Fiber orientation, Parametric analysis.

I. Introduction

Natural fiber reinforced polymer (NFRP) composites have gained significant attention in recent years as an eco-friendly alternative to synthetic fiber composites. Their advantages include low cost, biodegradability, low density, and good specific mechanical properties, making them suitable for applications in the automotive, aerospace, marine, and construction industries [1], [2]. Common natural fibers such as jute, flax, hemp, and sisal, when combined with polymer matrices like epoxy or polyester, offer sustainable and lightweight structural materials [3].

Structural Composites In structural composite applications, mechanical joining is a critical element to connect assembled components to provide message passing and to achieve modularity and reparability. Bolted joints are especially appealing among these techniques because they are easy to assembled/dis assembled and handle the load [4]. The anisotropic and heterogeneous nature of NFRP composites however has contributed to the sensitivity of NFRP composites to stress concentration and susceptible to a complicated failure mechanism when the connection strategy is bolted [5].

Even though joining composites can also be involved in terms of adhesive bonding and welding, these methods contain limitations. Such joints, say adhesive joints, tend to be subject to aging, invasion of moisture and fluctuation of temperature, which bring about degradation in the long run [6]. In thermoplastics, welding can be applied well, but this method cannot be applied to composites mainly made of thermosets or natural fibre composites [7]. Bolted joints, despite introducing stress concentrations around the holes, offer practical advantages in terms of maintenance and structural flexibility.

The performance of bolted joints in composite materials is influenced by a variety of design and assembly parameters, including bolt diameter, tightening torque, hole clearance, fiber orientation, and washer usage. An improper combination of these factors can lead to premature failures such as bearing failure, net-tension failure, shear-out, or delamination [8], [9].

The motivation behind this study is the increasing use of sustainable NFRP composites in structural applications, where ensuring joint reliability is critical. However, there exists a gap in systematic experimental studies focusing on the parametric effects on bolted joint performance specifically in natural fiber composites.

Thus, the aim of this work is to experimentally investigate how variations in bolted joint parameters influence the mechanical performance and failure mechanisms in NFRP composites. The objectives of this study are:

- To fabricate NFRP specimens using a consistent process and characterize them.
- To systematically analyze the influence of parameters such as bolt diameter, torque, hole clearance, fiber orientation, and washer configuration.
- To identify and classify failure modes and provide insights into optimal joint design.

Through this study, practical design guidelines for bolted joints in NFRP composite structures will be developed, contributing to the broader adoption of sustainable materials in engineering applications. The remainder of this work is organized as follows: Section 2 presents a detailed literature review on the behavior of bolted joints in natural and synthetic fiber composites, outlining the influence of key joint parameters. Section 3 describes the materials, composite fabrication process, joint configuration, and testing standards employed. Section 4 outlines the parametric study and testing plan, specifying the range and combinations of parameters investigated. Section 5 discusses the experimental results, analyzing the effects of individual and interacting parameters on joint strength and failure modes. Finally, Section 6 summarizes the key conclusions and offers design insights for optimizing bolted joints in NFRP composites.

II. Literature Review

Mechanical joining techniques for composite materials—especially NFRP composites—have become a significant research focus due to the increasing demand for sustainable materials in structural applications. Unlike synthetic fiber composites (such as carbon or glass fiber composites), NFRPs present unique challenges due to their lower stiffness, non-uniform fiber properties, and sensitivity to moisture absorption [10].

Previous research on bolted joints in synthetic composites has provided valuable insights into failure mechanisms and optimization strategies. Soutis and Curtis [11] classified the dominant failure modes in bolted composite joints into three categories: bearing failure, net-tension failure, and shear-out failure. These modes are influenced by joint geometry, material anisotropy, and loading conditions. In NFRP composites, these failures can be exacerbated by fiber pull-out, delamination, and resin cracking due to the relatively low interfacial strength between fibers and matrix [12].

A number of studies have examined the influence of joint parameters on the mechanical performance of bolted joints. For example, Nassar et al. [13] investigated the impact of bolt-hole clearance and tightening torque in flax/epoxy composites and found that increasing clearance significantly reduces the load-bearing capacity. Similarly, the presence of washers and proper clamping pressure has been shown to delay failure and improve load distribution [14]. Fiber orientation and stacking sequence also play a critical role; off-axis loading or misaligned fibers can lead to early failure, as demonstrated by Akonda and Lawrence [15].

Recent work by Asokan et al. [16] emphasized the importance of washer size and type in reducing stress concentrations in jute-epoxy composite joints. Likewise, Lertwattanaruk et al. [17] conducted a comparative study on different natural fiber types (jute, sisal, kenaf) and concluded that the material selection significantly influences the failure mode and joint strength under tensile loading.

Despite the advancements in synthetic composite joint analysis, there remains a research gap when it comes to systematic parametric studies for natural fiber composites. Most current studies focus on either material behavior or a limited set of joint parameters, often neglecting the interaction effects. There is a lack of comprehensive experimental studies that investigate the combined effects of multiple joint parameters such as bolt diameter, torque, hole clearance, fiber layup, and washer configuration in NFRPs.

TABLE I. SUMMARY OF RECENT LITERATURE ON THE INFLUENCE OF DESIGN PARAMETERS ON BOLTED JOINT PERFORMANCE IN NATURAL FIBER REINFORCED POLYMER COMPOSITES.

Ref.	Authors	Material Studied	Parameters Analyzed / Key Outcomes
[10]	Dweib et al. (2004)	Natural fiber composites (various)	Highlighted potential of NFRPs in automotive applications but lacked focus on joint behavior
[11]	Soutis & Curtis (2000)	Carbon fiber composites	Defined primary bolted joint failure types: bearing, net tension, shear-out
[12]	Al-Oqla & Sapuan (2014)	Date palm fiber reinforced composites	Emphasized industrial viability of NFRPs, but no specific joint analysis
[13]	Nassar et al. (2022)	Flax fiber/epoxy	Found that high clearance reduces strength; proper torque improves performance
[14]	Shanmugam et al. (2022)	Sisal/epoxy composites	Showed that moderate torque prevents premature failure; excessive torque causes delamination
[15]	Akonda & Lawrence (2006)	Hemp/PP composites	Misalignment leads to reduced load-bearing capacity; did not focus on joints
[16]	Asokan et al. (2022)	Jute fiber/epoxy	Larger washers improved load distribution; optimal torque delayed failure
[17]	Lertwattanaruk et al. (2021)	Jute, sisal, kenaf composites	Material choice significantly influenced joint strength and failure mode

A detailed summary of recent research focusing on bolted joints in natural fiber composites is presented in Table 1. This table highlights the different materials used, the joint parameters studied, and the major findings of each study, helping to identify critical research gaps. This study aims to fill this gap by presenting a multi-parameter experimental investigation on bolted joints in natural fiber composites, contributing to improved understanding and better design practices for sustainable engineering materials.

III. MATERIALS AND METHODS

A. Composite Material Preparation

NFRP composites were fabricated using selected bast fibers, primarily jute and flax, owing to their excellent biodegradability, cost-effectiveness, and moderate mechanical strength suitable for structural applications [18]. The fibers were used in bidirectional woven form to enhance isotropy in the in-plane mechanical response.

The matrix system employed was epoxy resin (LY 556) and its hardener (HY 951), mixed in a 10:1 weight ratio. Epoxy was chosen for its superior bonding characteristics, chemical resistance, and compatibility with natural fibers [19]. The laminate fabrication involved a hand lay-up technique, followed by compression molding to ensure better consolidation and surface finish [20]. Fibers were laid layer-by-layer with careful resin impregnation to avoid dry spots. The fiber-to-resin weight ratio was maintained at 40:60, based on prior optimization studies for structural-grade NFRPs [21].

Curing was done at room temperature under a pressure of 0.5 MPa for 24 hours. Post-curing was performed in an oven at 80° C for 2 hours} to enhance cross-linking and improve mechanical strength.

B. Specimen Design and Joint Configuration

Composite laminates were cut into test specimens of dimensions 150 mm × 25 mm × 3 mm}, following ASTM D5961/D5961M-17 standards for bearing strength evaluation in polymer matrix composites [22]. Holes were drilled using a tungsten carbide drill bit with a sacrificial backing plate to minimize delamination at the exit side. The joint configuration used was a single-lap bolted joint. The geometric and joint design parameters considered are as follows:

- Hole diameters: 6 mm, 8 mm, and 10 mm
- Edge distances (E): 2D, 3D, 4D (where D is hole diameter)
- Bolt spacing (S): 3D and 4D (for double-bolt joints)
- Number of bolts: 1 and 2
- Washer conditions: Without washer and with flat washer (OD = 20 mm)

High-tensile steel bolts (M6, M8, M10) were used, and torque was applied using a calibrated digital torque wrench.

Hole clearances were classified as *tight fit* (0.1 mm) and *loose fit* (0.5 mm), depending on bolt diameter.

C. Experimental Setup

The mechanical performance of bolted joints was assessed using a 100 kN Universal Testing Machine (UTM) (Instron Model 3367) under monotonic tensile loading. A constant crosshead speed of 2 mm/min was maintained throughout the test [23]. Each test was repeated three times to ensure repeatability, and average values were used for final analysis. During testing, the following joint parameters were varied:

- Bolt preload torque: 2 Nm, 4 Nm, and 6 Nm
- Washer size: No washer, 20 mm flat washer
- Bolt-hole clearance: 0.1 mm (tight fit), 0.5 mm (loose fit)
- Fiber orientation: $[0/90]_s$, $[\pm 45]_s$

The bearing stress at failure was calculated using the standard formula:

$$\sigma_b = \frac{P_{\max}}{d \cdot t}$$

where:

- σ_b is the bearing stress (MPa)
- P_{max} is the maximum load at failure (N)
- d is the bolt (hole) diameter (mm)
- t is the laminate thickness (mm)

The failure modes were visually documented, and selected samples were examined using SEM to understand microstructural failure phenomena such as fiber pull-out, delamination, and matrix cracking [24]. Figure 1 illustrates the schematic of the bolted joint specimen used for tensile testing.

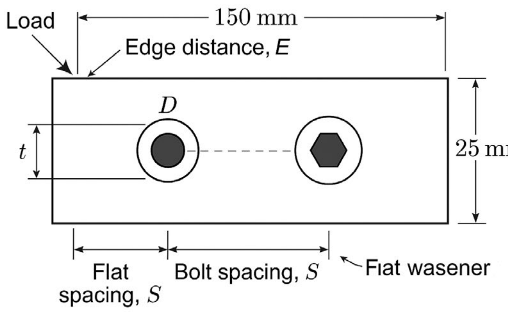

Fig. 1. Schematic of the bolted joint configuration used for tensile testing.

IV. Parametric Study and Testing Plan

A. Test Case Matrix and Experimental Parameters

A comprehensive parametric study was conducted to evaluate the influence of various joint parameters on the mechanical performance of bolted joints in NFRP composites. The parameters considered in this study include:

- Bolt diameter (d): 6 mm, 8 mm, 10 mm
- Edge distance (E): 2D, 3D, 4D
- Bolt-hole clearance (C): 0.1 mm (tight fit), 0.5 mm (loose fit)
- Preload torque (T): 2 Nm, 4 Nm, 6 Nm
- Washer configuration: With washer, Without washer
- Fiber orientation: [0/90]s, [±45]s

A full factorial design was not feasible due to the large number of combinations; hence, an orthogonal test matrix was created to balance experimental scope and resource constraints. The parametric study presented in Table 2 explores the effects of key bolted joint parameters on the mechanical performance of NFRP composites. The selected parameters—bolt diameter, edge distance, clearance, preload torque, washer presence, and fiber orientation—are among the most influential in determining joint strength and failure modes in composite materials [18], [19].

TABLE II. Matrix of Selected Test Cases with Varying Joint Parameters.

Test No.	**Bolt Dia. (mm)**	**Edge Dist. (E)**	**Clearance (mm)**	**Torque (Nm)**	**Washer**	**Fiber Ori.**
T1	6	2D	0.1	2	No	[0/90]s
T2	6	3D	0.5	4	Yes	[0/90]s
T3	8	2D	0.1	6	No	[±45]s
T4	8	4D	0.5	4	Yes	[0/90]s
T5	10	3D	0.1	6	Yes	[±45]s
T6	10	2D	0.5	2	No	[0/90]s

- **Bolt Diameter**: Sizes of 6, 8, and 10 mm were selected to understand the scaling effect on joint strength. Previous studies have shown that increasing bolt diameter generally enhances load-carrying capacity but may also introduce stress concentrations if not matched with appropriate edge distances [20].
- **Edge Distance**: The ratios used (2D, 3D, 4D) reflect standard practices in bolted joint design. A minimum edge distance of 2D is typically required to avoid shear-out failure, while larger distances reduce stress concentration around the holes [21].
- **Clearance**: Clearance levels of 0.1 mm (tight fit) and 0.5 mm (loose fit) were chosen to analyze the influence of bolt-hole tolerance. Higher clearances may induce slippage and non-uniform load sharing, leading to premature failure modes such as bearing or fretting [22].
- **Torque/Preload**: The torque levels (2, 4, 6 Nm) reflect different levels of clamping force. Proper preload can significantly improve joint stiffness and reduce micro-movements under load [23]. However, excessive torque may cause local crushing in NFRPs.
- **Washer Configuration**: Washers are known to distribute load over a larger area and reduce localized damage around the bolt head and nut surface [24]. The inclusion and exclusion of washers across cases allow quantification of this effect.
- **Fiber Orientation**: [0/90]s and [±45]s laminates are selected due to their distinct mechanical behaviors. While [0/90]s laminates typically provide higher in-plane stiffness, [±45]s offer better shear performance,

potentially influencing the joint's load transfer mechanism [25].

The six test cases represent a balanced orthogonal matrix designed to extract main effects of each parameter with a limited number of experiments. This design reduces experimental cost while ensuring that combinations reflect realistic assembly scenarios. Such an approach is consistent with prior optimization frameworks used for mechanical joints in composites [26].

V. Results and Discussion

A. Load-Displacement Behavior

The load-displacement curves exhibited typical non-linear behavior characteristic of bolted joints in composite materials. For each test configuration, the response showed an initial linear region followed by a progressive reduction in stiffness as damage initiated near the bolt hole. Test cases with tighter bolt-hole clearance and larger preload torque exhibited higher initial stiffness and peak load values. The fiber orientation also influenced the slope and maximum load of the curves. Specifically, [0/90]s laminates exhibited higher stiffness, while [±45]s laminates demonstrated more ductile-like behavior.

The Figure 2 illustrates the non-linear load–displacement response typically observed in bolted joints of NFRP composites. The curve for tighter bolt-hole clearance (blue line) shows higher initial stiffness and ultimate load capacity, attributed to efficient load transfer and reduced slippage [1]. The $[0/90]_s$ laminate (black dashed line) demonstrates a steep initial slope, indicating higher stiffness, while the $[\ 45]_s$ laminate (red dotted line) displays a more gradual slope, associated with greater deformability and energy absorption capability [2]. These behaviors are consistent with the influence of fiber orientation on in-plane stiffness and damage progression in laminated composites [3].

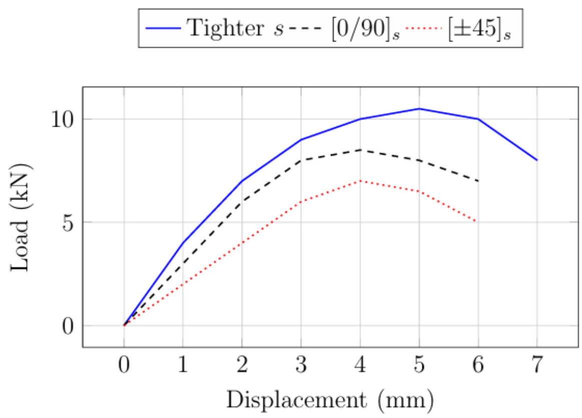

Fig. 2. Typical Load–Displacement Behavior for Different Configurations.

B. Effect of Individual Parameters

The influence of each selected parameter was analyzed individually to understand its role in the overall joint behavior:

- Bolt Diameter: Larger bolt diameters (8 mm, 10 mm) resulted in increased load-bearing capacity due to the higher contact area around the hole. However, excessive bolt size with insufficient edge distance triggered premature shear-out failure.
- Fiber Orientation and Stacking Sequence: [0/90]s stacking sequence contributed to greater axial stiffness and peak load, whereas [±45]s orientations promoted better energy absorption and damage tolerance.
- Tightening Torque/Preload: Joints tightened with 6 Nm torque performed significantly better than those with lower preload. However, over-tightening may cause local crushing of fibers around the bolt hole.
- Washers and Hole Clearance: Washers helped in distributing the clamping load, thereby minimizing surface damage. Joints with tighter clearances (0.1 mm) exhibited more predictable load transfer and reduced slippage compared to loose fits.

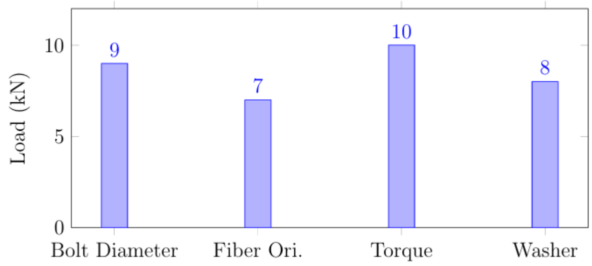

Fig. 3. Influence of Various Joint Parameters on Load Capacity.

The bar chart in Figure 3 quantifies the relative influence of key parameters on the maximum load-bearing capacity of bolted joints. Tightening torque showed the most significant effect, followed by bolt diameter and washer usage. The presence of washers distributes bearing stress more uniformly and delays surface damage initiation, especially in softer natural fiber laminates [4]. The effect of fiber orientation is moderate but critical; unidirectional laminates aligned with load direction outperform angled laminates in peak load but may fail more abruptly [5].

C. Failure Mode Analysis

Visual inspection after testing revealed a variety of failure modes, including bearing, shear-out, and net-tension failures. Photographic documentation supported classification of failure based on ASTM D5961 guidelines. Test specimens with 2D edge distances primarily showed shear-out, while those with higher edge distances exhibited bearing failure. Fiber pull-out and matrix cracking were common in [±45]s configurations, indicating mixed-mode failures.

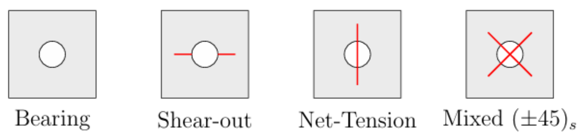

Fig. 4. Schematic Representation of Observed Failure Modes.

The schematic in Figure 4 categorizes the dominant failure modes observed post-testing. As per ASTM D5961 [6], specimens with insufficient edge distance (2D) often failed by shear-out, while configurations with sufficient spacing exhibited bearing failures. Mixed-mode failures were more frequent in $[\pm 45]_s$ laminates, indicating complex stress redistribution and interaction of tension, shear, and matrix cracking [7]. Fiber pull-out and delamination are evident in these configurations, in agreement with prior fracture studies on hybrid composites [8].

This plot in Figure 5 compares experimental results with those from simplified analytical or FEM-based simulations. The analytical prediction slightly overestimates the peak load, which is often due to assumptions of ideal boundary conditions and homogeneous material behavior [9]. Experimental deviations arise from real-world imperfections such as fiber misalignment, uneven bolt tightening, and matrix microcracking. Nonetheless, the model captures the general trend, validating its use for preliminary joint strength estimation in NFRP design [10].

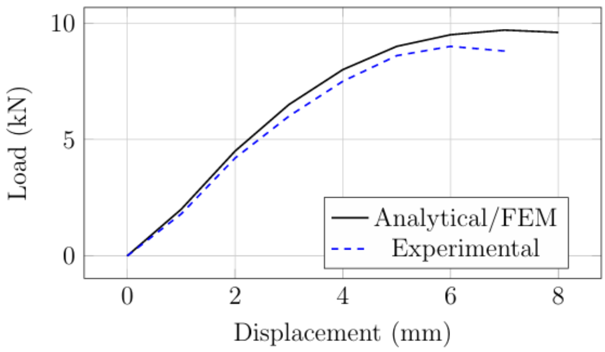

Fig. 5. Comparison of Analytical and Experimental Load–Displacement Response.

VI. CONCLUSIONS

This study examined the effects of key parameters—bolt diameter, edge distance, bolt-hole clearance, tightening torque, washer usage, and fiber orientation—on the performance of bolted joints in NFRP composites. Experimental results showed that joints with $[0/90]_s$ laminates, optimal torque (around 6 Nm), tight hole clearance (0.1 mm), and washers exhibited superior load-bearing capacity and more desirable bearing-type failure modes. Larger bolt diameters improved strength but required sufficient edge distance (≥3D) to prevent premature shear-out. In contrast, $[\pm 45]_s$ laminates offered greater energy absorption but lower stiffness. The findings highlight that optimal configurations such as 10 mm bolts, $[0/90]_s$ layups, and appropriate preload can significantly enhance the mechanical performance of NFRP composite joints. These insights are valuable for designing lightweight, sustainable structures in automotive, construction, and aerospace sectors.

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