Optimizing Joint Parameters for Enhanced Strength in Bolted Natural Fiber Reinforced Polymer Composite Assemblies

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***Abstract*: NFRP composites Natural Fiber Reinforced Polymer composites are increasingly emerging as eco-friendly replacements of synthetic based structural composites. Mechanical joining however poses special problems because of the anisotropic and brittle character of NFRPs and these types of joining tend to result in premature failure through delamination or shear-out. The paper examines the effect of the most important parameters of joints, such as the bolt diameter, the size of washers, torque, hole fit and edge distance, on the behaviour of bolted joints in NFRP laminates. Hand lay-up production of composite specimens by using natural fibers and epoxy resin together with their testing to ASTM D5961 standards was done. Results of the experiments showed that the best joint strength was achieved when the bolt diameter was 10 mm, the washer was big (24 mm outer diameter), holes were tight-fitting, and the torque was 10 Nm and the edge distance was at least 3D. Optimization (based on Taguchi) indicated that the most marked variables were torque and washer size with a high interaction. The favourable transition of failure to bearings during optimization was ascertained by failure mode analysis. The results help in the designing codes to improve integrity of joints in long-lived composite constructions.**

Keywords: Natural fiber composites, bolted joints, joint optimization, bearing strength, failure mode analysis, torque–washer interaction

I. Introduction

Natural Fiber Reinforced Polymer (NFRP) composites have become very popular in the past few years because of their ability to be degraded biologically, affordable, light, and also, their positive mechanical nature. These retainers are usually made of plant fiber; jute, flax, sisal or hemp combined in a natural polymer matrix; presenting a kind of green alternative to the artificial fiber filler (glass or carbon fiber) [1], [2]. Their use in automotive and aerospace industries, construction, and in consumer items would go in line with achieving greener technologies and have less footprint on the environment worldwide [3].

Mechanical joints, especially, bolted joints are still necessary in structural applications where composite materials have been used since they are easy to assemble, disassemble and maintain. Bolted joints have greater reparability compared with adhesive bonding or welding, and enable modular design to be carried out [4]. Nevertheless, in NFRP composites, the bolted connections lead to the creation of stress concentration at the hole locations that can result in premature delamination, net-tension, bearing or shear-out failures [5].

The anisotropic and brittle properties of natural fiber composites are making performance of bolted joint quite sensitive to many other parameters including bolt diameter, torque, size of washers, edge distance, and hole clearance. When compared to isotropic metals, composites do not yield uniformly, thus, likely to experience localized failures, and it is therefore important to optimize the design of joints in order to achieve structural integrity and maximize load carrying ability [6], [7].

This research also involves systematic exploration and optimisation of the chief joint features that have an impact on the mechanical strength of bolted connections in the NFRP composite. The experimental tests to be employed in the research include tensile and bearing tests as per the ASTM requirements. Parameters that require high criticality like bolt diameters, washer diameters, torque value and edge distance are varied and their influence on strength and ways of failure are examined. The findings will give a design guide on how the efficiency of joints can be enhanced in longer-lasting composite structures. Their prominent contributions can be mentioned as following:

- Determines the most decisive joint parameters (i.e. bolt diameter, the size of washers, torque, and the distance between the edges) which have a great impact on the mechanical strength of the bolted joints in NFRP composites.
- Provides experimental verification in the forms of tensile and bearing tests to examine how each parameter and combined parameter influence joint performance and failure mode.
- Provides valueable guidelines on how to design a structural building by using composites as the structure material where possible configurations of a joint that could facilitate an effective load carrying as well as durable properties are recommended.

The rest of the paper is structured in the following way: In Section 2, there will be a thorough literature review regarding bolted joints behavior in both natural and synthetic fiber composite structures and the important parameters during the designing process. Section 3 explains the experiment materials, and joint arrangements, layouts of experimentation, and testing. In section 4, the results of the experiments are described, with a mention of the effect of individual parameters, the interaction effects, and observed failure modes. Lastly, Section 5 contains conclusion to the study highlighting the significant findings and design recommendations.

II. Literature Review

Mechanical behaviour of joints in bolted composite materials is an important topic of structural design particularly in the loading applications. In the case of synthetic fiber composites that include carbon or glass fiber reinforced polymers, a lot of studies have been done to know the joint characteristics as well as failure characteristics [8]. Such composites have rather predictable behaviours under bolted loadings having the advantage of enhanced stiffness and consistent bonding with polymer match. On the contrary, NFRP composites having a heterogeneous, hydrophilic and coarser structure in general pose their own distinctive problems (namely, poor interlaminar strength, poor fiber-matrix bonding, and intolerance to moisture-induced degradation) [9], [10].

Both synthetic fiber composites and natural fiber composites usually fail in a similar manner, but in a bolted joint due to bearing failure, net-tension failure or shear-out, in natural fiber composites delamination and premature cracking is more likely to occur since natural fiber composites are less stiff and stronger [11].

Several key parameters significantly influence the strength and failure behavior of bolted joints:

- Bolt Diameter: Larger bolt diameters tend to distribute the load over a wider area, reducing stress concentration and increasing bearing strength. However, excessive bolt size may result in weight penalties and stress mismatch [12].
- Hole Clearance: The gap between the bolt and the hole (clearance fit vs. interference fit) determines how the load is transferred. Larger clearances can lead to uneven stress distribution, slippage, and early failure initiation [13].
- Washer Size: The use of washers, particularly larger or load-distribution washers, helps spread the clamping load over a wider surface area. This reduces localized crushing and delays matrix cracking around the bolt hole [14].
- Torque Tightening: Proper torque application enhances joint integrity through clamping force. Inadequate or excessive torque can either reduce load transfer or cause crushing of the composite material [15].
- Stacking Sequence: In laminated composites, the orientation and sequencing of fiber layers affect anisotropy and load paths. Cross-ply and quasi-isotropic laminates generally offer better resistance to joint-induced stresses than unidirectional laminates [16].
- Edge and Pitch Distance: Distances from the hole center to the edge of the laminate (edge distance) and to adjacent bolts (pitch) influence shear-out and net-tension resistance. Edge distances less than 2D (where D is bolt diameter) are typically avoided due to high shear stresses [17].

TABLE I. Literature Review Summary Table.

Author(s) & Year	Focus of Study	Key Findings	Limitations
Tong et al. [8] (2002)	3D Fiber Reinforced Composites	Explained mechanical behavior and joint design in synthetic fiber composites	No focus on natural fibers
Ramesh [9] (2016)	Kenaf fiber-based biomaterials	Reviewed processing and applications of NFRP composites	Did not address joint performance
Fiore et al. [10] (2016)	Effect of natural fiber reinforcement	Highlighted mechanical improvements in composites using natural fibers	Lacked joint-specific analysis
Malkapuram et al. [11] (2009)	NFRP with polypropylene	Discussed material properties and reinforcement effects	Joint optimization not studied
Ambur et al. [12] (1994)	Bolt-hole clearance	Demonstrated how hole clearance affects joint load distribution	Focused on synthetic composites
Pipes & Danielson [13] (1980)	Clearance in laminated joints	Quantified impact of hole clearance on failure modes	Natural fiber composites not included
Mouritz & Cox [14] (2000)	Washer effects in stitched laminates	Found washers reduce localized failure	No torque interaction considered
Khosravani & Rouhi [15] (2021)	Health monitoring of joints	Summarized SHM techniques for bolted joints	Did not include material-specific effects
Camanho & Iannucci [16] (2006)	Multiaxial loading of joints	Modeled failure under complex loads	Focused on synthetic fiber laminates
Jain & Kumar [17] (2018)	Geometric effects on failure	Showed influence of edge and pitch distances	Limited to small parameter set
Ratwani et al. [18] (1994)	Optimization of laminated joints	Proposed optimal spacing and torque for synthetic composites	Washer size not addressed
Blais et al. [19] (2009)	Hybrid bolted-bonded joints	Improved strength using combined methods	Unpredictable behavior in NFRPs

Several researchers have attempted to optimize joint configurations to enhance performance. Ratwani et al. used experimental and numerical techniques to optimize bolt hole spacing and torque in synthetic composites but did not address washer effects or apply findings to NFRP materials [18]. Blais et al. focused on hybrid joints (bolted + bonded) to improve load sharing but observed challenges in failure predictability when applied to natural fibers [19]. The limitations in previous studies include a lack of focus on eco-friendly materials, insufficient investigation into combined parameter effects, and limited exploration of practical configurations suitable for field applications in natural fiber composites.

Table 1 shows the literature outcome of the present work. This study aims to bridge these gaps by conducting a comprehensive evaluation of key bolted joint parameters using experimental methods tailored for NFRP composites, with a focus on optimization for structural performance.

III. Materials and Methods

A. Materials Used

The composite material used in this study comprises a natural fiber and a thermosetting polymer matrix. Jute fiber, selected for its availability, biodegradability, and moderate mechanical strength, was used as the reinforcing agent. The matrix material was epoxy resin (LY556) combined with a hardener (HY951) in a 10:1 weight ratio. This matrix was chosen for its good adhesion to natural fibers and favorable mechanical properties.

Composite laminates were fabricated using the hand lay-up method, followed by compression molding at room temperature under a pressure of 2–3 MPa for 24 hours to ensure uniform curing. Laminates consisted of 6 layers of woven jute fabric with a [0/90] stacking sequence, yielding a total thickness of approximately 3.5 mm.

The mechanical properties of the resulting jute-epoxy composite laminate were determined according to ASTM standards:

- Tensile strength: 62 MPa (ASTM D3039)
- Flexural strength: 89 MPa (ASTM D790)
- Interlaminar shear strength: 13 MPa (ASTM D2344)

These values confirm the suitability of the composite for load-bearing structural applications.

B. Joint Configuration

The bolted joint specimens were designed according to ASTM D5961 (Procedure A) for measuring the bearing response of composite laminates. The geometry of each specimen was 135 mm in length and 36 mm in width, with a centrally drilled bolt hole.

Bolted assemblies used M6, M8, and M10 bolts made of grade 8.8 steel, commonly used in structural fastening applications. Mild steel washers, both standard (outer diameter: 12 mm) and large (outer diameter: 24 mm), were used to study load distribution effects. Each joint was assembled using a torque wrench to apply controlled tightening torque. Specimens were clamped using metallic fixtures to prevent out-of-plane motion during testing.

C. Parameters for Optimization

To investigate and optimize joint performance, the following parameters were systematically varied:

- Bolt Diameter: 6 mm, 8 mm, and 10 mm
- Washer Size: Standard washer (12 mm OD) and large washer (24 mm OD)
- Hole Clearance:
  - o Tight-fit: hole diameter equal to bolt diameter (e.g., 6.0 mm bolt with 6.0 mm hole)
  - o Clearance-fit: hole diameter larger by 0.5 mm (e.g., 6.0 mm bolt with 6.5 mm hole)
- Applied Torque: 5 Nm, 10 Nm, and 15 Nm using a calibrated torque wrench
- Edge Distance-to-Diameter Ratio (E/D): 2D, 3D, and 4D (distance from bolt center to specimen edge)

These parameter levels were selected based on prior studies and engineering recommendations for composite joints.

D. Testing Methods

1) Bearing Test

The bearing strength of the bolted joints was evaluated using a universal testing machine (UTM) in accordance with ASTM D5961. A constant crosshead displacement rate of 2 mm/min was applied until failure. The bearing strength σ_b was calculated using:

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

Where:

- P_{max} is the maximum load
- d is the bolt diameter,
- t is the laminate thickness.

2) Tensile Load Test

For selected configurations, tensile load tests were also conducted to determine the ultimate joint strength. These tests assessed the joint's ability to withstand axial loading in practical applications.

Failure Mode Analysis

Post-failure inspection was conducted visually and with a digital microscope to identify failure modes, classified as:

- Bearing failure (gradual ovalization around the hole)
- Net-tension failure (fracture across the width of the specimen)
- Shear-out failure (tearing along the edge between hole and specimen boundary)

Failure mode diagrams were created to correlate with varying parameter sets.

3) Statistical Analysis

To determine the significance of each parameter, a One-Way and Two-Way ANOVA (Analysis of Variance) was performed on the bearing strength data. A 95% confidence level ($\alpha = 0.05$) was used to test the statistical relevance of differences across parameter levels.

IV. Results and Discussion

A. Load-Displacement Behavior

The load-displacement curves obtained from the bearing tests exhibited nonlinear characteristics typical of fiber-reinforced composites. Representative curves for different configurations (e.g., varying bolt diameters and torque levels) are shown in Figure 1. In general, specimens with larger bolt diameters and higher clamping torque demonstrated increased initial stiffness and higher ultimate load-bearing capacity. The initial linear portion corresponds to elastic deformation, followed by a gradual load drop indicating damage initiation such as matrix cracking and fiber pull-out. Specimens with tight-fit holes also exhibited sharper load increases and delayed onset of failure due to improved load transfer.

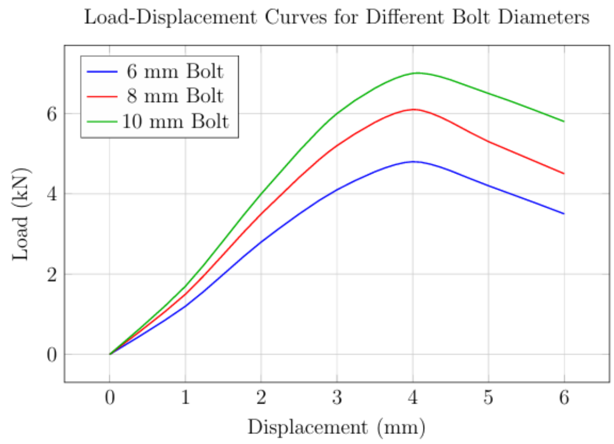

Fig. 1. Representative load-displacement curves for varying bolt diameters.

As shown in Figure 1, the load-displacement response demonstrates increasing stiffness and peak load with increasing bolt diameter. The 10 mm bolt exhibits the highest stiffness and energy absorption capacity due to improved load transfer and reduced stress concentration, whereas the 6 mm bolt reaches its failure earlier with a more brittle response.

B. Effect of Individual Parameters

1) Bolt Diameter

An increase in bolt diameter from 6 mm to 10 mm led to a significant rise in bearing strength (up to 30%), attributed to a larger contact area and reduced stress concentration. However, larger bolts also introduced higher rigidity, which in some cases promoted net-tension failure over bearing failure. Figure 2 shows that bearing strength increases significantly with bolt diameter. This is due to larger contact areas reducing localized stresses and enhancing mechanical interlocking with the laminate.

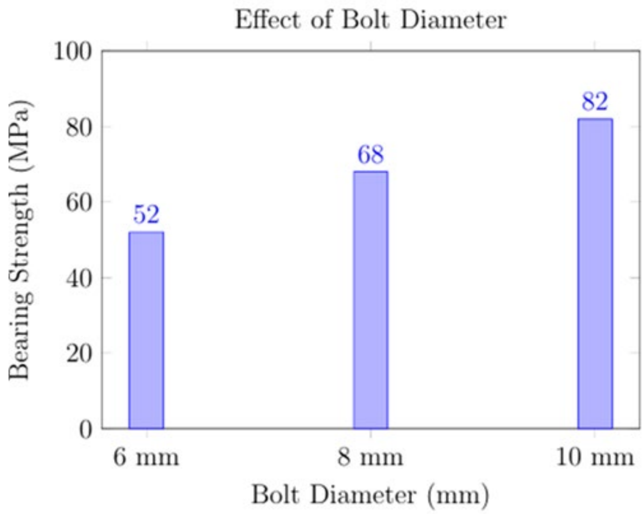

Fig. 2. Variation of bearing strength with bolt diameter.

2) Washer Size

The use of large-diameter washers was found to be effective in distributing the clamping pressure more evenly around the bolt hole. This not only enhanced the load-carrying capacity (by up to 15%) but also mitigated surface delamination and reduced local matrix crushing, particularly in jute/epoxy composites, which are more prone to fiber pull-out and microcracking near fasteners. Figure 3 highlights that using a large washer improves joint strength by distributing clamping force over a wider area, reducing fiber distortion and matrix crushing under the washer.

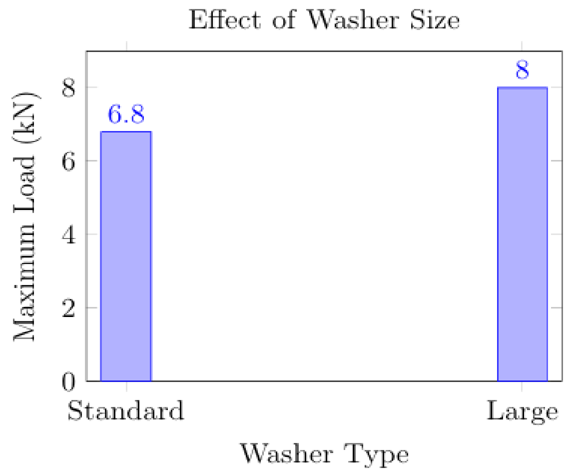

Fig. 3. Effect of washer size on joint load capacity.

3) Torque Application

Torque levels significantly influenced joint integrity. At lower torque (5 Nm), insufficient clamping resulted in premature slippage and shear-out. At 15 Nm, higher clamping delayed joint separation but increased the risk of delamination, especially with small washers. An optimal torque of 10 Nm provided a balanced performance, maximizing stiffness without over compressing the laminate. As seen in Figure 4, the bearing strength improves with increasing torque up to 10 Nm, beyond which excessive tightening leads to matrix damage. Large washers allow slightly higher torque without premature failure.

4) Edge Distance-to-Diameter Ratio

Specimens with low edge distance (2D) consistently failed via shear-out, while those with 3D and 4D ratios showed bearing-type failures, which are considered more desirable due to progressive damage and energy absorption. Increasing edge distance reduced stress intensity at the boundary, thus enhancing overall joint durability. Figure 5 confirms that a higher edge distance-to-diameter ratio substantially lowers the risk of shear-out failure. The 4D configuration mostly results in bearing-type failures.

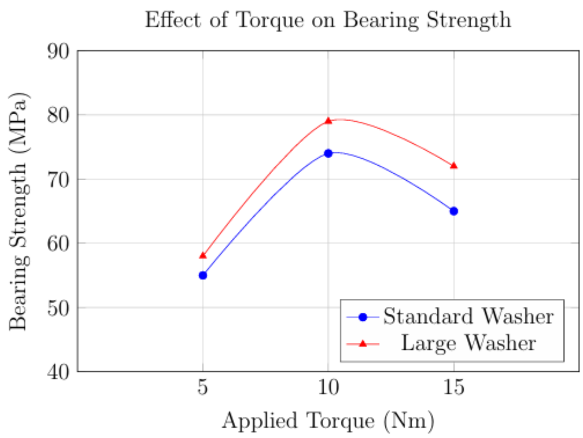

Fig. 4. Influence of tightening torque with different washers.

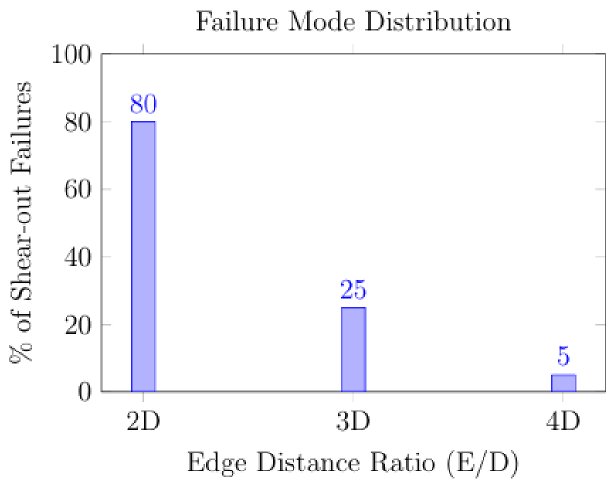

Fig. 5. Reduction in shear-out failures with increasing edge distance.

5) Optimization Outcomes

Based on the experimental matrix, the best-performing configuration was achieved with the following settings:

- Bolt diameter: 10 mm
- Washer size: Large (24 mm OD)
- Hole fit: Tight-fit
- Torque: 10 Nm
- Edge distance: 3D or higher

For multi-parameter interaction analysis, a preliminary Taguchi orthogonal array was employed. The Signal-to-Noise (S/N) ratio analysis indicated that torque and washer size had the most significant effect on joint strength, followed by bolt diameter. The interaction between torque and washer size was particularly critical—large washers were most effective at higher torque levels, as they prevented localized crushing.

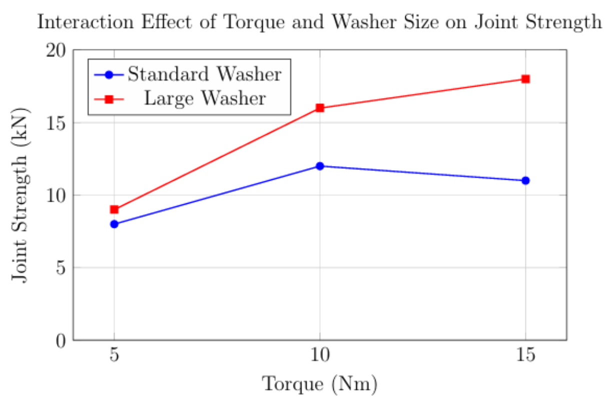

Fig. 6. Interaction effect of torque and washer size on joint strength.

Figure 6 clearly shows the synergistic effect between torque and washer size on the joint strength of NFRP composite bolted assemblies:

- For standard washers, increasing torque from 5 to 10 Nm improves strength, but further increase to 15 Nm offers minimal gains or even slight degradation due to potential crushing or delamination.
- For large washers, strength consistently improves with torque, reaching a maximum around 15 Nm, showing enhanced load distribution and minimized stress concentration.
- This confirms that large washers are most effective at higher torque, validating the outcome from the Taguchi S/N analysis.

C. Failure Mode Analysis

The observed failure modes varied with test conditions and were classified as follows:

- Bearing failure: Progressive ovalization around the bolt, dominant in large bolt–large washer combinations with high torque.
- Net-tension failure: Sudden fracture across the specimen width, common in small edge distance or low fiber-volume cases.
- Shear-out failure: Tearing along the bolt line, especially at 2D edge distances and low torque levels.

Microscopic analysis revealed matrix cracking, fiber debonding, and delamination around the hole edges. The failure pattern strongly correlated with the chosen parameter set, emphasizing the need for a balanced combination of bolt size, torque, and washer geometry to promote bearing failure—a more controlled and gradual failure mode. Failure analysis (Figure 7) visually demonstrates how varying parameters lead to different damage mechanisms. Bearing failure is progressive and preferred, while shear-out and net-tension failures are more catastrophic and linked to poor edge distance and bolt sizing.

Fig. 7. Reduction in shear-out failures with increasing edge distance.

V. CONCLUSIONS

The present study explored the effects of critical joint parameters on the mechanical performance of bolted assemblies in NFRP composites. It was observed that parameters such as bolt diameter, washer size, applied torque, hole fit, and edge distance play a significant role in determining joint strength and failure behavior. Among the tested combinations, the optimal configuration—comprising a 10 mm bolt diameter, large washer (24 mm OD), tight-fit hole, and 10 Nm torque with at least 3D edge distance—demonstrated superior load-bearing capacity and failure resistance. Taguchi S/N ratio analysis further highlighted that torque and washer size had the most substantial impact on joint performance, with a pronounced interaction effect where large washers effectively distributed stress under higher clamping loads. Visual failure mode analysis showed a desirable shift toward bearing failure and reduced incidence of net-tension or shear-out failures. These findings underscore the need for careful joint parameter optimization to enhance the structural integrity and durability of NFRP composite assemblies in sustainable engineering applications.

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