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A CASE STUDY ON STRUCTURAL BEHAVIOUR OF BOLTED JOINTS IN GFRP TRANSMISSION LINE TOWERS

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ABSTRACT

This thesis deals with the case study on the properties of GFRP (Glass Fiber Reinforced Polymer) In this Thesis we use the GFRP to find out the behaviour of the final product madeby this material which is line transmission tower. Due to the rapid population growth and rapid urbanization, the natural resources are depleting day by day. So, the natural aggregates are very hard to obtain. So many people are opting to use the GFRP (Glass Fiber Reinforced Polymer) instead of the conventional iron or steel channels. The cost of conventional iron or steel channels as compared to GFRP is also very high due to the high demand of it in construction works. GFRP will reduce the quarrying and mining of iron and steel ores thereby reducing the use of natural resources excessively. The land surface can be prevented from any unwanted excavation and hence ecological disturbances will be reduced to conserve the conventional natural iron ore for other important construction works. The compression and the tensile tests are carried out in the thesis to find out the behaviour of the different types of the joints and channel sections with different types of connections. And the result is carried out and accordingly the conclusion is given. This study focuses on the structural behaviour of bolted joints in Glass Fiber Reinforced Polymer (GFRP) transmission line towers, specifically investigating the use of GFRP for these structures as an alternative to traditional steel.

Key Words: GFRP (Glass Fiber Reinforced Polymer), Transmission tower, Urbanization, Construction.

I. INTRODUCTION

1.1 Background

Glass Fiber Reinforced Polymer (GFRP) is a composite material consisting of glass fibers embedded in a polymer matrix such as epoxy, polyester, or vinyl ester. It is widely used in civil engineering due to its high strength, durability, and resistance to environmental degradation.

Transmission line towers traditionally use steel; however, increasing demand for sustainable and lightweight materials has led to the exploration of GFRP structures.

1.2 Problem Statement

Bolted joints are critical components in transmission towers. In GFRP structures, these joints become weak points due to:

- Stress concentration near holes
- Anisotropic material behaviour
- Brittle failure mechanisms

1.3 Objectives

- To study mechanical properties of GFRP
- To analyze behaviour of bolted joints
- To identify failure modes
- To evaluate load–displacement characteristics
- To develop design recommendations

1.4 Scope of Study

The study focuses on:

- Experimental analysis of bolted joints
- Influence of geometric parameters
- Structural behaviour under loading

II. LITERATURE REVIEW

Glass fiber reinforced plastics (GFRP) parts are made by filament winding techniques, sometimes require machining. Even though GFRPparts produced by molding processes require machining to facilitate dimensional control for easy assembly and control of surface quality for functional aspects. Machining of GFRP parts include turning, drilling, milling, grinding etc. The machining of GFRP composites differs significantly from that of machining of conventional materials due to the composite's anisotropic and highly abrasive nature of typical fiber reinforcement [14]. Thus it is desirable to investigate behavior of GFRP during the machining process. The present study is focused on the machining characteristics of GFRPcomposites. In general, good surface finishing of GFRP composites will be necessary, because the surface roughness has received serious attention for many years. From the available literature it has been noticed that, surface roughness is considered as an important design feature in many situations such as parts subjected to fatigue loads, precision fits, fastener holes and aesthetic requirements. In addition to tolerances, surface roughness impose one of the most critical constraints for selection of machines and cutting parameters in process planning [18]. Until now most of the studies on the cutting of GFRP have been concentrated on the mechanism of tool wear and surface roughness [19]. However for the practical machining of GFRP, it is necessary to determine the optimal machining parameters to achieve less tool wear, good surface finish, etc,.

1. Wang et al., 2025

"Experimental investigation on GFRP double-bolt single-lap joints (DBSLJs)": This experimental work tested double-bolt single-lap GFRPspecimens under quasi-static and post-impact tensile loading to characterise damage initiation and progressive failure. The authors manufactured standard GFRPlaminates with controlled hole geometry, varied bolt spacing and edge distance, then performed low-velocity impact followed by tension-after-impact tests to simulate real service damage.

Results showed that post-impact bearing and net-tension capacities drop significantly with reduced edge distance and that impact-induced delamination governs early stiffness loss. The study quantifies how geometric parameters (w, e1, d0) shift failure modes between bearing, shear-out and net-tension, providing practical guidance for minimum spacing in bolted GFRP designs. The authors also provide load–displacement curves and failure maps useful for designers assessing damage tolerance.

2. S Xiang et al., 2024

"Investigation on fatigue behavior of GFRP hybrid bonded/bolted single-lap joints": This paper presents extensive fatigue testing of hybrid (bonded + bolted) GFRP single lap joints under shear loading, combined with non-destructive monitoring (Acoustic Emission and 3D- DIC) and FE modelling. Specimens included single-bolt, 4-bolt and 9-bolt layouts to show the effect of bolt count; fatigue life was split into distinct stages (initial steady period, rapid adhesive damage, steady GFRP degradation, final rapid failure). The experiments demonstrated that hybridization delays crack initiation and extends life versus purely bolted joints, while increasing bolt count greatly reduces stiffness degradation. Acoustic emission signatures correlated well with adhesive debonding and fibre breakage events, enabling earlier detection of critical damage. The paper therefore argues for hybrid solutions and multi-bolt layouts when fatigue resistance is critical.

3. Wang et al., 2024

"Static and fatigue behavior of hybrid bonded/bolted GFRP joints under tensile

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loading": Through a controlled set of static tensile and constant-amplitude fatigue tests on nine single-lap hybrid specimens, this study quantifies ultimate bearing loads, stiffness degradation trends and S–N curves for GFRP hybrid joints. The authors used instrumented tests and DIC to map strain concentration around bolt holes, showing that the bolted region dominates strength once adhesive damage begins.

Fatigue testing revealed that most life is consumed in slow adhesive degradation, with catastrophic GFRP plate failure occupying only a small fraction of cycles — a useful insight for maintenance scheduling. Design takeaways include recommended bolt counts and conservative bearing factors for fatigue design of hybrid GFRP connections.

4. D. Martins et al., 2025

"Shear-out failure of GFRP single-bolted double-lap connections: experimental investigation and reliability-based code calibration": This experimental campaign focused on single-bolt double-lap GFRPconnections to characterise shear-out and bearing failures across a wide range of geometries and loading conditions. The paper reports detailed material characterization, load–displacement responses, observed failure modes (bearing, shear-out, net-tension) and statistical variability of ultimate loads. Importantly, the authors apply a reliability-based calibration of existing code equations (e.g., CEN/TS models), showing where standard design formulas are unconservative for GFRP and proposing calibrated resistance factors for safer design. This work is particularly valuable for structural engineers who need probabilistic safety margins for bolted GFRPjoints.

5. Yang et al., 2025

"Study on the performance of adhesive–bolt hybrid connections between GFRPplates and steel members" (PMC, 2025): This experimental study examines adhesive-bolt hybrid connections joining GFRPplates to steel, combining single-bolt tests and multi bolt layouts under static and cyclic loading. The authors compared purely bolted, purely bonded, and hybrid configurations, assessing failure modes (adhesive debonding, bearing, bolt shear, GFRP fracture) and the influence of pre-load/tightening torque and washer geometry. Key findings show that hybrid connections can markedly improve load capacity and stiffness while reducing stress concentrations at bolt holes; however, time-dependent effects in GFRP (creep/relaxation) reduce preload effectiveness at elevated temperatures. The paper recommends hybrid joints with appropriate surface treatment and preload control for durable steel–GFRP interfaces.The proposed project involves the construction of an L-shaped office building within the premises of Bharat Heavy Electricals Limited (BHEL). This initiative is part of BHEL's ongoing infrastructure development plan aimed at enhancing administrative efficiency, improving workspace quality, and accommodating growing operational demands.

The L-shaped architectural design has been strategically selected to optimize the available land area, ensure better natural lighting and ventilation, and promote functional space utilization. The building will be constructed using modern engineering practices, adhering to all relevant IS codes, environmental standards, and safety regulations.

This project underscores BHEL's commitment to modernizing its infrastructure and providing a productive, sustainable, and employee-friendly work environment. The building will house multiple administrative departments, meeting rooms, and support facilities, all designed to foster collaboration and efficiency.

III. MATERIALS REQUIRED

3.1 Research Methodology

The present study adopts a quantitative research methodology to investigate the structural

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behaviour of bolted joints in Glass Fiber Reinforced Polymer (GFRP) transmission line towers. Quantitative research is primarily concerned with the collection and analysis of numerical data in order to explain and predict engineering phenomena with accuracy and objectivity. In this research, the methodology is designed to measure the performance of GFRP bolted joints under different loading and geometric conditions through systematic experimentation and statistical analysis. The approach ensures that the results obtained are reliable, reproducible, and suitable for generalization in practical engineering applications.

The methodology involves a sequence of steps beginning with material selection, specimen preparation, experimental testing, and data analysis. GFRP pultruded sections commonly used in transmission towers are selected, and bolted joint specimens are fabricated with varying parameters such as bolt diameter, edge distance, and plate thickness. These specimens are then tested under controlled conditions using a Universal Testing Machine (UTM) to simulate real-life structural loading. The load–displacement behaviour, stiffness characteristics, and failure modes are recorded and analyzed to understand the performance of the joints.

3.2 Deductive & Inductive Techniques

The research methodology incorporates both deductive and inductive techniques to ensure a comprehensive understanding of the problem. Deductive techniques involve the use of existing theories, literature, and previously established knowledge to formulate hypotheses regarding the behaviour of GFRP materials and bolted joints. This approach moves from general concepts to specific assumptions, allowing the researcher to develop theoretical expectations based on earlier studies.

On the other hand, inductive techniques are used to validate these hypotheses through experimental investigation. In this approach, observations and experimental data are collected and analyzed to determine whether the hypotheses hold true in practical scenarios. The inductive process moves from specific observations to broader generalizations, thereby confirming or rejecting the assumptions made during the deductive phase. The combination of both techniques ensures a balanced research approach that integrates theory with experimental validation.

3.3 Type of Data Used

The study utilizes both primary and secondary data to achieve its objectives. Primary data is obtained directly from experimental testing of GFRP bolted joint specimens. This includes measurements of load, displacement, strain, and failure characteristics recorded during testing. The primary data is essential for validating hypotheses and understanding the actual behaviour of the joints under different conditions. Secondary data, on the other hand, is collected from existing literature, research papers, journals, and technical publications related to GFRP materials and composite structures. This data is used to build the theoretical framework of the study, identify research gaps, and support the development of hypotheses. The integration of both primary and secondary data enhances the accuracy and credibility of the research findings.

3.4 Deductive Technique & Determination of Hypothesis

The deductive technique plays a crucial role in formulating hypotheses for this research. Based on the review of literature and existing knowledge on machining and structural behaviour of GFRP, several hypotheses are developed to predict the influence of various parameters on the performance of the material. These hypotheses relate to factors such as drill diameter, feed rate, tool wear, temperature, and vibration during machining processes, as well as their impact on damage and structural performance.

The hypotheses are formulated as logical statements that describe the expected relationships between variables. For instance, it is assumed that an increase in drill diameter or feed rate may lead to higher thrust force and increased damage to the GFRP material. Similarly, higher temperatures and tool wear are expected to adversely affect the quality of machining and structural integrity. These hypotheses serve as a foundation for experimental investigation and are later tested using inductive methods to determine their validity.

3.5 The Inductive Approach

The inductive approach is employed to experimentally verify the hypotheses developed through deductive reasoning. This involves conducting controlled experiments on GFRP specimens and analyzing the results to observe patterns, relationships, and trends. The experiments focus on parameters such as drilling conditions, material properties, and joint configurations, which influence the behaviour of GFRP structures.

Through systematic observation and data analysis, the inductive approach helps in identifying the actual effects of different variables on the performance of GFRP materials. The results obtained from experiments are compared with the predicted outcomes to determine whether the hypotheses are valid. If the experimental findings support the hypotheses, they are accepted; otherwise, they are modified or rejected. This approach ensures that the conclusions drawn from the study are based on empirical evidence and practical observations.

IV. RESULTS AND DISCUSSION

Comparison of Experimental and Theoretical Results

The comparison between experimental and theoretical results provides a clear understanding of the structural behaviour of bolted joints in GFRP transmission line tower applications. The theoretical strengths of the joints were calculated based on analytical expressions considering bearing failure, net-section tension failure, and shear-out failure modes as per relevant composite design provisions. These calculations were based on assumed uniform stress distribution and ideal material behaviour. However, the experimental results obtained from the Universal Testing Machine (UTM) revealed variations due to practical factors such as stress concentrations around bolt holes, local crushing of GFRP fibres, bolt slip, and slight misalignment during loading. In most specimens, the experimental ultimate load was slightly lower than the theoretical predicted value. This reduction can be attributed to the anisotropic nature of GFRP, fibre breakage near the bolt hole, matrix cracking, and progressive damage mechanisms that are not fully captured in simplified theoretical models. In some cases, the stiffness obtained experimentally was lower than the theoretical stiffness due to initial bolt-hole clearance and seating deformation. The load–displacement curves showed nonlinear behaviour before failure, whereas theoretical calculations assumed linear elastic behaviour up to ultimate load.

The governing failure mode observed experimentally generally matched the theoretically predicted critical failure mode, particularly bearing failure in specimens with adequate edge distance. However, for specimens with smaller edge distances, premature shear-out or net- section failure was observed, indicating the sensitivity of joint performance to geometric parameters. The percentage variation between experimental and theoretical ultimate loads was within an acceptable range, validating the design approach while highlighting the need for suitable safety factors in practical design.

Overall, the comparison demonstrates that theoretical models provide a reasonably accurate estimation of joint capacity, but experimental validation is essential for composite bolted joints due to their complex failure mechanisms and material heterogeneity.

Theoretical values were calculated based on analytical equations for bearing, net-tension, and shear-out failure modes.

Experimental ultimate load was generally slightly lower than theoretical predictions.

Difference occurred due to:

- Stress concentration around bolt holes
- Anisotropic behavior of GFRP
- Fibre breakage and matrix cracking
- Bolt-hole clearance and initial slip

Experimental load–displacement curves showed nonlinear behavior, while theoretical models assumed linear elastic behavior.

Stiffness obtained experimentally was often lower due to seating deformation and bolt slip.

The predicted governing failure mode mostly matched the experimentally observed failure mode.

Edge distance and bolt spacing significantly influenced variation between theoretical and experimental results.

Percentage variation between results was within acceptable limits, validating the analytical design approach.

Experimental validation is essential for GFRP joints because composite materials exhibit progressive and complex failure mechanisms.

Suitable safety factors are required in practical design to account for uncertainties.

Effect of Edge Distance – Important Points

- ❖ Edge distance is the distance from the center of the bolt hole to the free edge of the GFRP plate.
- ❖ It significantly influences the strength, stiffness, and failure mode of bolted joints.

Small edge distance:

- Leads to premature shear-out failure.
- Causes high stress concentration near the edge.
- Reduces ultimate load carrying capacity.
- Produces brittle and sudden failure.
- Results in lower joint efficiency.

Adequate edge distance:

- Promotes bearing failure, which is more gradual and desirable.
- Increases ultimate load capacity.
- Improves stress distribution around the bolt hole.
- Enhances joint stiffness and ductility.
- Excessively large edge distance:
- Does not significantly increase strength beyond a certain limit.
- Increases material usage and weight.
- Reduces economic efficiency.

Edge distance must satisfy code-recommended minimum limits to ensure safe and efficient joint performance.

V. CONCLUSION

Experimental behaviour of bolted joints in GFRP transmission line towers was carried out to evaluate the strength, stiffness, and failure characteristics of mechanically fastened composite connections. Based on the analytical design, structural analysis, and experimental investigation, the following conclusions are drawn:

The theoretical calculations were able to reasonably predict the ultimate load capacity and governing failure modes of the bolted joints. However, experimental results showed slight reductions in strength compared to theoretical values due to stress concentrations, bolt-hole clearance, fibre breakage, matrix cracking, and

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the anisotropic nature of GFRP. This confirms that analytical models provide good initial estimates but require experimental validation for composite structures.

Edge distance, bolt diameter, and plate thickness were found to significantly influence joint performance. Specimens with adequate edge distance predominantly exhibited bearing failure, which is a more gradual and desirable mode of failure. In contrast, specimens with smaller edge distances showed premature shear-out or net-section failure, resulting in lower load- carrying capacity. Increasing edge distance improved joint strength and stiffness up to an optimum limit.

The load–displacement behaviour of the joints demonstrated nonlinear characteristics prior to failure, indicating progressive damage in the GFRP material. Experimental stiffness values were slightly lower than theoretical predictions due to initial slip and seating deformation of bolts.

Overall, the study confirms that GFRP bolted joints can safely be used in transmission line tower applications when properly designed. With appropriate geometric parameters and safety factors, GFRP structures can provide a lightweight, corrosion-resistant, and structurally efficient alternative to conventional steel towers.

The findings of this project contribute to better understanding and improved design practices for bolted connections in composite transmission tower systems.

Theoretical calculations reasonably predicted the ultimate strength of bolted joints.

Experimental ultimate load was slightly lower than theoretical values.

Variation occurred due to stress concentration, bolt slip, and anisotropic behavior of GFRP.

Edge distance significantly influenced strength and failure mode.

Adequate edge distance promoted bearing failure (desirable mode).

Smaller edge distance caused premature shear-out or net-section failure.

Joint stiffness from experiments was lower due to bolt-hole clearance and seating deformation.

Load–displacement curves showed nonlinear behavior before failure.

Governing failure modes observed experimentally matched theoretical predictions in most cases.

Properly designed GFRP bolted joints are suitable for transmission line tower applications.

GFRP structures offer advantages such as lightweight, corrosion resistance, and durability.

Experimental validation is essential for safe and efficient composite joint design.

Research Gap Identified

- Insufficient experimental data on bolted joints under actual tower load conditions.
- Limited comparison between theoretical predictions and experimental validation.
- Need for optimized joint design guidelines specific to GFRP transmission structures.

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