Central Power Research Institute
Vol. 19(2)/225-231, December 2023
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v19i2.1150
Power Research

Experimental Investigation of Lateral Load Test on Diagonal Braced 3M Glass Fiber Reinforced Polymer Transmission Tower

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Abstract

Over the past decades, numerous research and development studies worldwide have focused on various civil engineering applications involving composite materials. Presently, recent investigations have explored the utilization of Glass Fiber Reinforced Polymer (GFRP) members in tower panels, composite cross arms in towers, full-scale 66 kV FRP double circuit towers, FRP towers created through filament winding techniques, GFRP triangular base communication towers, GFRP square base tower panels with bolted connections and strength and stability assessments of Glass Fiber Polyamide (GFP) towers and carbon fibre reinforced towers. The susceptibility of conventional TLT members to theft, where thieves often cut and steal them, prompted the suggestion to consider TLTs constructed with different materials. The study for examining the behavior of hybrid joints in angle-to-angle connections, with an 'e/d' ratio is 5. The well-performing hybrid joint has been implemented in a GFRP tower model and subjected to lateral loading to assess the effectiveness of such joints.

Keywords: Glass Fiber Polyamide (GFP), Glass Fiber Reinforced Polymer (GFRP), Transmission Line Towers (TLT)

1. Introduction

The degradation of conventional transmission line towers in the aggressive environmental zones across the world demands innovative materials for making such important structures. Glass Fiber-Reinforced Polymer (GFRP) is one of the proven materials emerging into power transmission structures elsewhere. It is well known for its corrosion resistance and lightweight properties. The pultrusion process facilitates the production of GFRP sections, ensuring a cost-efficient method that enables the mass production of straight, long, and consistently structured components. While GFRP sections are generally considered reliable, there are limitations in the design criteria's reliability. GFRP angles find application in self-supporting lattice-type communication towers, encompassing primary, leg and secondary bracings. In contrast, conventional tall transmission towers supporting overhead power lines are typically constructed from steel members. These towers exhibit diverse shapes and sizes within high-voltage AC and DC systems, with heights ranging from 15 to 55 meters. Transmission towers come in four distinct types: transposition, terminal, suspension, and tension. Their primary function is to elevate power conductors to a safer height above ground level, contributing to the management of natural calamities. The design of transmission towers is an integral component of various engineering concepts and plays a crucial role in the ongoing development of civilization.

Polyzois DJ *et al.*,[1] demonstrated the feasibility of constructing a low-cost prototype full-scale Fiber-Reinforced Polymer (FRP) guyed tower using GFRP angle members produced through the filament winding technique. Godat A *et al.*,[2] explored the economic benefits of incorporating W, I, and circular sections of FRP pultruded members in

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Transmission Line Towers (TLTs). Hernández-Corona R *et al.,*[3] highlighted the potential of using suitable polymeric composite materials as an alternative to steel bracing in transmission line towers, ensuring structural stability and deterring theft of redundant steel members. Selvaraj M *et al.,*[4-6] investigated to understand the buckling properties and characteristics of GFRP members as lattice towers. Also, he explored the performance of composite cross-arms in a 66 kV transmission tower concerning conventional steel cross-arm members. The findings suggested that employing FRP cross-arms could potentially decrease the corridor distance from 18 m to 15 m. This research outcome opens avenues for further investigations into compact transmission lines in the future, offering the possibility of increased height for such studies in India. In another investigation, it was noted that Right of Way (RoW) can be reduced by 17% and height reduced by 16% using FRP towers in comparison to traditional steel towers.

Three 24-meter-high equilateral triangular communication towers using Glass Fiber-Reinforced Polymer (GFRP) members have been tested by Prasad Rao *et al.*[7] The towers had GFRP leg members with a 60° angle and bracing members with a 90° angle. It was observed that the 60° angle tower failed due to torsional-flexural buckling in the leg member, while the final failures in trials 1 and 2 were caused by de-bonding of layers and trial 3 failed due to shearing of the cross-section. For GFRP 90° angle bracing, flexural buckling occurred, and final failures were attributed to end crushing and shear deformation at the connections.

In their study, Balagopal R *et al.,*[8] revealed the construction of a GFRP pultruded angle member square-based communication x-braced tower panel measuring 1.5x1.5x1.25 meters in height. The primary objective was to investigate the buckling behaviour of axially loaded leg members and bracing members with bolted connections. The researchers identified that the failure of the panel stub member was attributed to excessive bending stress in the compression leg member. Consequently, they recommended eliminating the stub-free length portions in GFRP tower panels to enhance their structural integrity. M. Raghunathan *et. al.,*[9] explored the tensile capacity of single bolted connections between GFRP angle sections, incorporating gusset plates in their investigation. Bhowmik *et al.,*[10-12] have discussed the deterioration of components in steel transmission towers, proposing alternative materials like carbon fibre epoxy, Glass Fiber Polyamide (GFP) composite, etc. These materials were considered for a 132 kV transmission tower and modelled using finite element analysis software. Under the above background, it was denoted to take published articles so far that have exclusively addressed bolted Glass Fiber Reinforced Polymer (GFRP) plate-to-plate connections. Introducing adhesive into bolted connections (hybrid) reduces failure and enhances connection performance. However, no prior research has investigated GFRP structural angle member connections with hybrid joints. The study for examining the behavior of hybrid joints in angle-to-angle connections, with an 'e/d' ratio is 5. The well-performing hybrid joint has been implemented in a GFRP tower model and subjected to lateral loading to assess the effectiveness of such joints.

2. Materials

The GFRP plates and angles used are sourced from a private production firm in India, with the GFRP pultruded angle specimen measuring 50x50x6 mm. The material structure includes alternating layers of unidirectional E-glass fibres in the pultrusion direction, bi-directional woven roving mats for the angles and randomly oriented E-glass strand mats (CSM). Both sections are embedded in an isophthalic polyester resin/matrix. The gusset plate and angle profile maintain a constant thickness of 6 mm for all connections.

3. Test Specimens

For the Angle-to-Angle connection, the specimen was cut to dimensions of 240x40x6 mm by ASTM D3039 standards[13]. A cutting machine was used to cut the specimen, followed by grinding the edges with a grinding machine. The specimen's centre line was marked, and an edge distance of 40 mm was maintained based on an e/d ratio of 5. A total of fifteen specimens were prepared for the test. These specimens were further divided into three types of connections, as illustrated in Figure 1, for the tensile test:

Angle-to-Angle Bolt Connection.

Angle-to-Angle Hybrid Connection (Local glue).

Angle-to-Angle Hybrid Connection (Epoxy).

3.1 Bolt Connection

The Angle with bolted connections for the set of 5 specimens was prepared as shown in Figure 1(a) marked the centre line of the specimen and maintained the edge distance of 40 mm and made holes to the marked area and connected the using 8 mm bolts, nuts and washers.

3.2 Hybrid Connection (Local Glue)

The angle member relates to bolted connection and local glue which is the mixture of flex kwik and baking soda as shown in Figure 1(b). The prepared 5 sets of specimens were marked the centre line and edge distance of 40 mm and made a hole of that marked space in 8 mm after that some scratches in the plates on alternative sides to make a bonding to the flex kwik and the specimen and adding some amount of baking soda to the top of the specimen. After the 8 mm bolts, nuts and washers are fixed and tightened.

3.3 Hybrid Connection (Epoxy)

The angle member relates to a bolted connection and epoxy resin between the two plates for the set of 5 specimens as shown in Figure 1(c). The ratio of mixing the epoxy resin and hardener is 1kg of epoxy mixed with 150 ml of hardener and it will be fully mixed. The epoxy resin is applied between the connected two plate sections and tightened the bolt again.

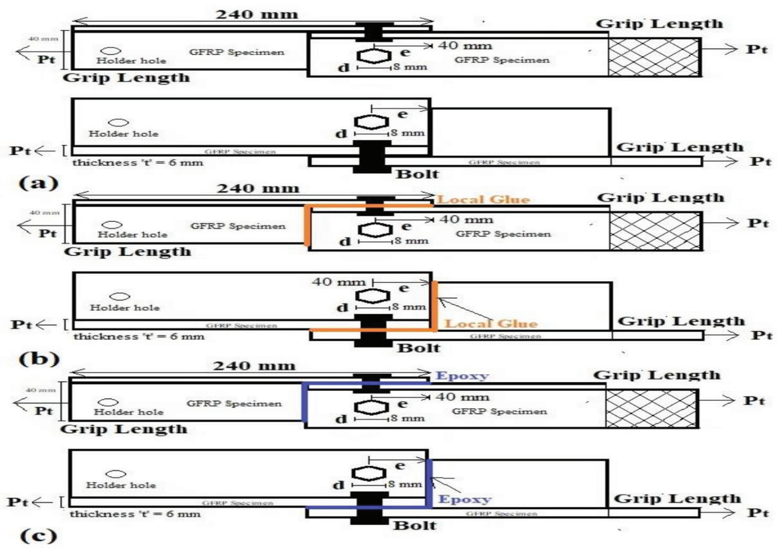

Figure 1. Angle-to-angle connection: **(a)** Bolt connection **(b)** Hybrid (local glue) connection **(c)** Hybrid (epoxy) connection.

4. Result and Discussion

4.1 Performance of Angle-to-Angle Connection Member

From the review of the literature, it is reported that there are four common failure modes such as bearing failure, shear-out failure, cleavage failure and net-tension failures that occur in single-bolted connections. The angle-to-angle connection tested specimens are shown in Figures 2 to 4. The tensile performance of GFRP angle-to-angle connection test results is presented in Table 1.

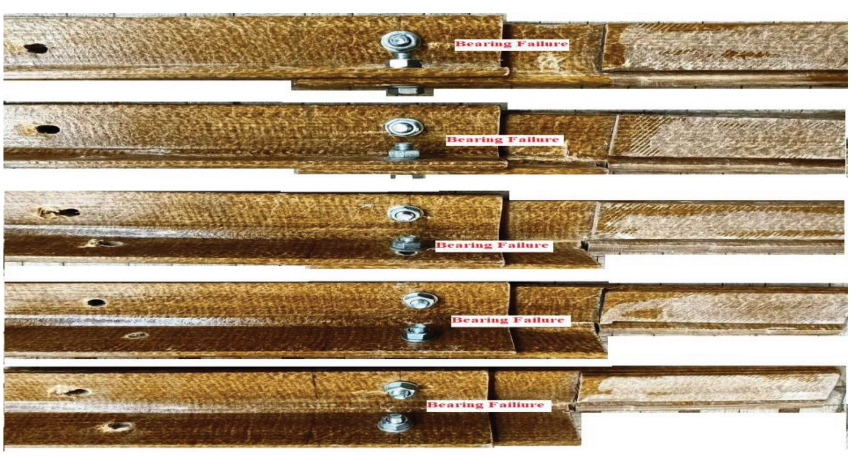

Figure 2. Angle-to-angle bolt connection tested specimens.

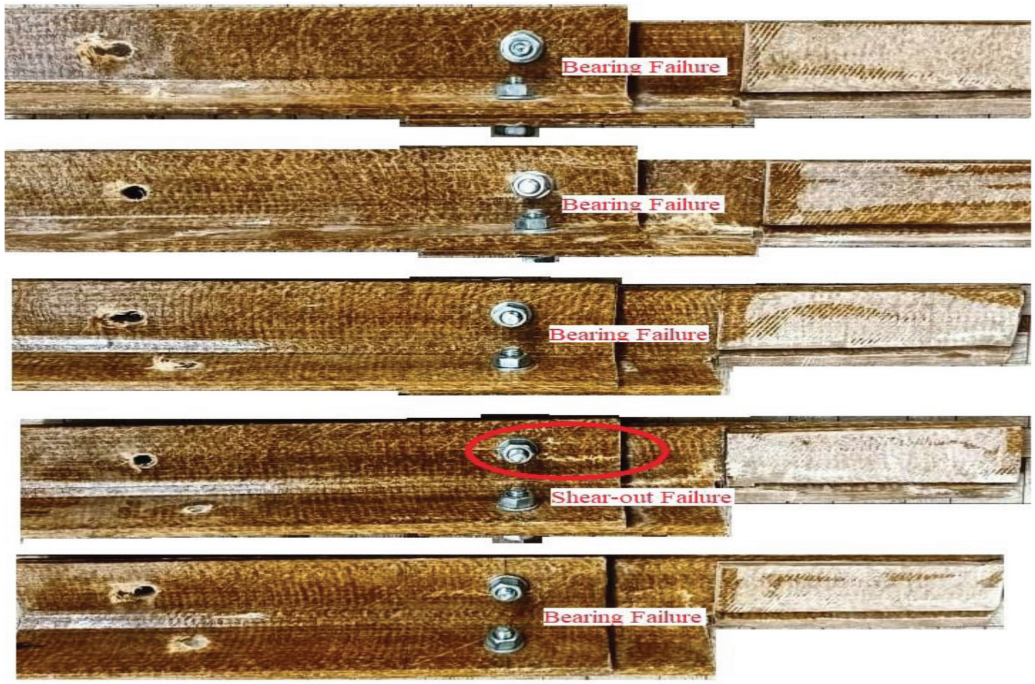

Figure 3. Angle-to-angle hybrid connection (local glue) tested specimens.

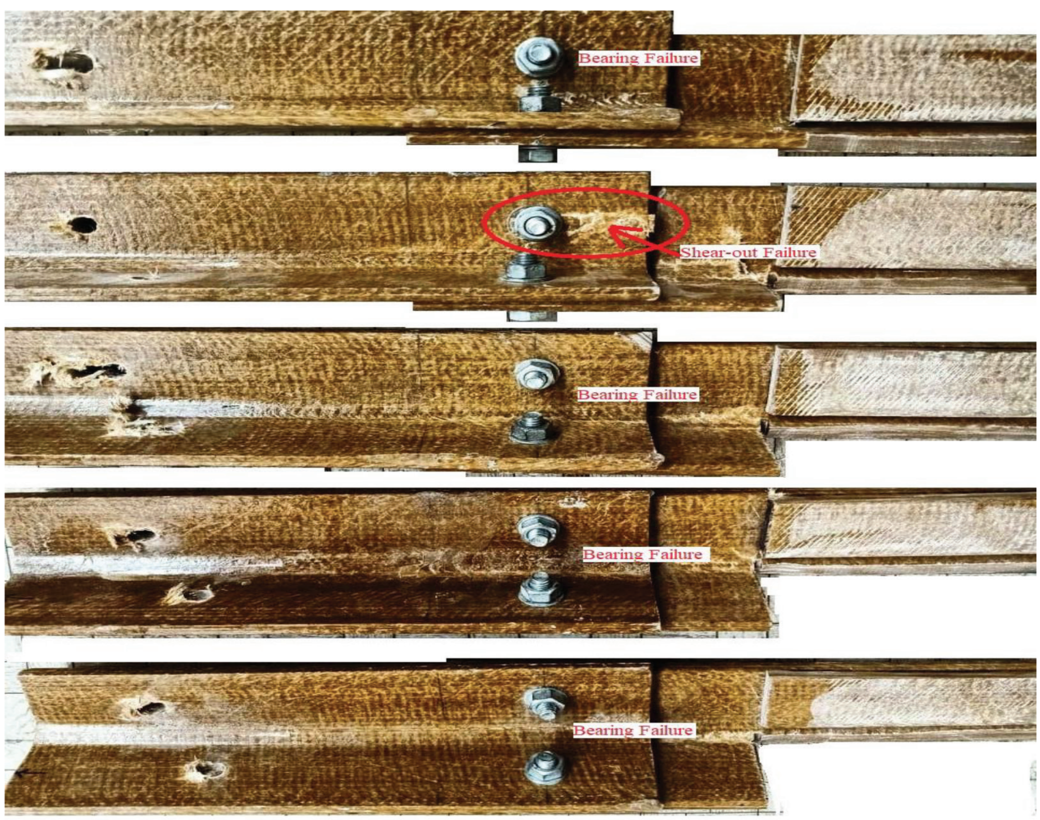

Figure 4. Angle-to-angle hybrid connection (epoxy) tested specimen.

Table 1. GFRP angle-to-angle connection tension test result

Section	Specimen ID	Failure Load in kN	Mean Failure Load in kN	Elongation at Peak	Average Elongation at Peak	Failure Mode
Angle-to-angle bolt connection	AB1	32.270	31.26	10.65	6.08	Bearing Failure
	AB2	25.880		1.590		Bearing Failure
	AB3	34.490		1.660		Bearing Failure
	AB4	31.490		9.160		Bearing Failure
	AB5	32.190		7.360		Bearing Failure
Angle-to-angle hybrid (Local glue) connection	AG1	34.030	32.41	10.14	7.53	Bearing Failure
	AG2	31.880		8.950		Shear out Failure
	AG3	33.240		9.430		Bearing Failure
	AG4	31.200		6.020		Bearing Failure
	AG5	33.190		3.130		Bearing Failure
Angle-to-angle hybrid (Epoxy) connection	AE1	34.110	33.83	7.010	8.83	Bearing Failure
	AE2	34.100		10.630		Bearing Failure
	AE3	34.880		9.300		Bearing Failure
	AE4	33.460		9.210		Shear out Failure
	AE5	32.580		8.010		Bearing Failure

The experimental results show that the failure loads increase when adding adhesive (epoxy) along with bolt connection increasing by about 8.2% and the elongation at peak load increasing by about 45.2% for e/d ratio 5 in the angle-to-angle connections.

In the angle-to-angle bolted connections, 100% of connected specimens only fail bearing failure whereas in hybrid (local glue) and hybrid (epoxy) connections, 20% of connected specimens fail shear-out failure with maximum failure loads and 80% of connected specimens fail bearing failure with maximum failure loads. The elongation percentage at peak load also increased.

4.2 Performance of 3m GFRP Tower

The design load is chosen to create the wind load at the top of the tower model typically at 3 m height. Under the lateral load condition, the tower model is verified. The load is applied in 5 kN increments until the design load is 45 kN is reached. The tower model withstood the design load successfully. From the load vs deflection behaviour, the tower model experienced a maximum force, which is greater than 45 kN. The deflection of the tower model exhibits 38 mm for 45 kN loads. The deflection behaviour of steel tower with GFRP tower is furnished in Figure 6.

The key observations made from the numerical analysis are as below.

- GFRP tower with hybrid connection exhibited less deflection than steel tower by 3mm at 3m height top of the tower.
- The GFRP tower with adhesive connection exhibited a deflection of 10.142 mm which is 1.5 mm less than the steel tower and 0.3 mm higher than the GFRP tower with hybrid connections.
- The GFRP tower with bolt connection exhibited a deflection of 11.24 mm which is 0.4 mm less than the steel tower and 1.4 mm higher than the GFRP tower with adhesive connections.

From the deflection behaviour of the GFRP transmission line tower model, the maximum deflection of the tower from numerical analysis exhibits close agreement with experimental results. Also, the tower withstood design loads by experimental and numerical analysis.

Figure 5. Testing on the GFRP transmission tower.

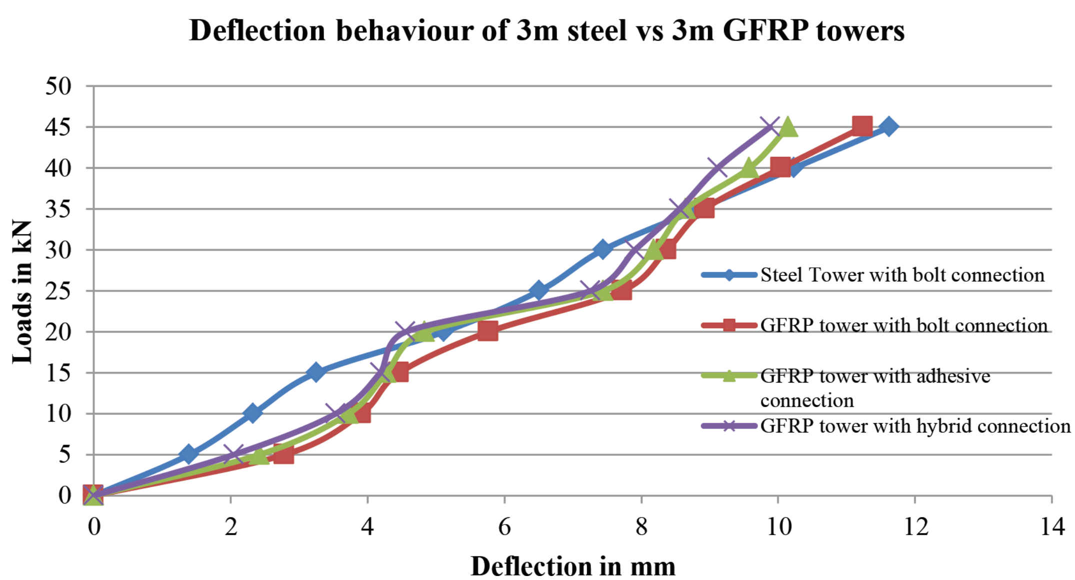

Figure 6. Deflection behaviour of 3m Steel tower vs 3m GFRP towers.

5. Conclusion

The behaviour of various connections in the GFRP members of TLT has been investigated. The following observations were made.

- In the angle-to-angle connection, and bolted connection, 5 specimens exhibit shear-out failure mode bearing failure mode. Hybrid (local glue) connection, 1 specimen exhibits shear-out failure and 4 specimens exhibit bearing failure. Hybrid (epoxy) connection, all 5 specimens exhibit bearing failure. The hybrid (epoxy) connection has more joint efficiency for angle-to-angle connections.
- As for the lateral load application on a 3 m GFRP tower, the test results exhibited that the hybrid connection has a very low deflection of 17.05 mm. The deflection of the GFRP tower is 73% less than

the steel tower and the maximum stress developed in the GFRP tower is 30% less than the steel tower.

- Hence it can be concluded that GFRP composite TLT with a hybrid connection can withstand wind loads. The GFRP tower is economical for the long term while considering the recurring maintenance cost of a conventional steel TLT.

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