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Reference

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ABSTRACT

The aim of this paper is to investigate the crushing and tensile performance of built-up glass fiber–reinforced polymer (GFRP) pultruded angle sections under compression and tension loads. For the compression test, two GFRP angle sections of size 50 × 50 × 6 mm were selected and maintained the *e*/*d* ratio of 5. GFRP angle sections were connected by two-bolt, three-bolt, four-bolt, adhesive, hybrid two-bolt, hybrid three-bolt, and hybrid four-bolt connections. For the tension test, single-lap joint and single-bolt connections were considered. The tension test is performed by angle-to-angle connection with an *e*/*d* ratio of 5. Also, the joints were connected by single-bolt connection, hybrid single-bolt with local glue, and hybrid single-bolt with epoxy connection. Based on the studies, the best joint and connection were considered, and a transmission line tower with various connections is modeled and proposed using ANSYS.

Keywords

glass fiber–reinforced polymer angle, crushing, tensile, connections, stability

Introduction

The economical design of communication towers needs an alternate emerging material, such as steel. The glass fiber–reinforced polymer (GFRP) is one of the materials with corrosion resistance and light weight.[1] In the maintenance side, GFRP requires only one fourth of the expenditure incurred by steel and hence it has an attractive economical features. The GFRP sections are produced through the pultrusion process, which is cost efficient and provides mass production of straight, long, and constant structural sections. The section of GFRP is considered a reliable one, but there are limitations in the reliability of the design criteria. The GFRP angles are self-supporting lattice type communication towers and includes primary, legs, and secondary bracings. Generally, the overhead power line is supported by a tall transmission tower made of steel. Also, the transmission tower is named as the steel lattice transmission tower, which makes different shapes and sizes in high voltage of AC and DC system.[2–5] Usually, the height of this tower ranges from 15 to 55 m. These towers are made up of materials such as wood and concrete rather than steel. There are four types of transmission tower: transposition, terminal, suspension, and tension type. The purpose of the transmission tower is to carry power conductors into a safer height from the ground. Also, these towers manage natural calamities. Naturally, transmission tower design is included in all engineering concepts and plays a vital role in the development of civilization.[6]

Polyzois, Raftoyiannis, and Ochonski[7] have reported that the construction of a low-cost prototype full-scale fiber-reinforced polymer (FRP) guyed tower using the filament winding technique is possible. Godat et al.[8] have investigated the use of W, I, and circular sections of FRP pultruded angle sections in transmission line towers (TLTs) results in economy. Hernández-Corona and Ramírez-Vázquez[9] have reported that the use of suitable polymeric composite material as an alternative to steel bracing using transmission line tower can withstand the structural stability and also to prevent the theft of the steel redundant angle sections from these towers. It is commented that conventional TLT parts are cut and stolen by the thieves in the country. Hence, it was suggested to go for TLT with different materials.

Selvaraj, Kulkarni, and Rameshbabu[10] have conducted theoretical, analytical and experimental investigations on advanced composite materials, including FRP-pultruded angle sections in lattice towers, to find the buckling properties and characteristics of the angle sections. It can be a replacement for conventional steel towers to avoid corrosion problems and reduce maintenance expenses due to continuous exposure in hostile environmental conditions. Selvaraj, Kulkarni, and Babu[11] have also investigated the performance of composite cross arms (CA) of a 66-kV transmission tower instead of conventional steel CA angle sections. It was commented that with FRP CA, the corridor distance could be decreased from 18 m to 15 m. The result of this investigation offers more light to undertake investigation on compact transmission lines in future.

Zekavati, Jafari, and Saeedi[12] have introduced a new type of composite CA for power transmission lines. Here, the lattice type of CA structure includes composite pultruded tubes and mechanically bolted joints. In order to design a correct model and to guarantee the performance of the introduced CA, experimental and finite element (FE) methods were used. It was proved from the result that the introduced composite lattice CA structure was able to tolerate applied mechanical loads and to replace the conventional steel CA.

A 66-kV overhead power transmission line tower built with FRP composite material for the first time in India was tested at Central Power Research Institute, Bengaluru, by Selvaraj, Kulkarni, and Rameshbabu,[13] who have also carried out experimental analysis on a full-scale FRP 66-kV tower under mechanical loading. They have erected a full tower with different cross sections of FRP leg angle sections, bracings, and CA angle sections. From previous research investigations, the full FRP tower was assembled with suitable joining techniques with steel plates and end clamps. Requirement of Right of Way can be reduced by 17 %, and the height of the tower can be reduced by 16 % in the FRP tower when compared with a steel tower.

Prasad Rao, Rokade, and Balagopal[14] have erected three 24-m-high equilateral triangular GFRP communication towers, where the GFRP leg angle sections' subtended angle was 60° and for bracing angle sections was 90°. From the failure investigation of 24-m triangular base GFRP telecommunication towers, the authors have suggested understanding the basic material properties of new materials in order to make TLT structures out of square-based tower, because more restraint to leg angle sections from secondary bracings is experienced. The observation has been made that the cause of failure from the GFRP 60° angle tower was torsional-flexural buckling in the leg member and the final failures for trial 1 and 2 tower were due to de-bonding of layers of the stitched mat. The final failure for trial 3 was due to shearing of the cross section. The strength capacity is found to be affected due to eccentricity creation by providing lap connection when load is applied in lap connection, an eccentricity is set in resulting reduction in strength capacity. When GFRP 90° pultruded angle was used as a bracing member, it is observed that it buckled under flexure and eventually due to crushing and shear deformation at the connection point.

Balagopal, Prasad Rao, and Rokade[15] reported that GFRP-pultruded angle member square-based communication x-braced tower panel of size 1.5 × 1.5 × 1.25 m height have been erected to find the buckling behavior of the axially loaded leg member and bracing member with bolted connections. They observed the reason for the failure of the panel stub member is found to be more bending stress in the compression leg member, and authors suggested eliminating the stub free length portions for the GFRP tower panel. Raghunathan, Senthil, and Palani[16] have investigated the tensile capacity of single-bolted connections between GFRP angle sections with gusset plates. Bhowmik and Chakraborti[17,18] have reported the degradation of components in steel transmission towers can be taken care if such angle sections were replaced by various composite materials such as carbon fiber epoxy, glass fiber polyamide (GFP) composite material etc., which is taken for the 132-kV transmission tower as alternate materials and modeled using FE analysis software. The International Council on Large Electrical Systems has come up with a technical brochure on transmission line structures with FRP under working group B2.61. The technical copy has elaborately discussed various aspects of FRP material development, FRP structure manufacturing methods, FRP applications of lattice structures, FRP construction methods, and testing of FRP materials and structural components, including FRP research and development needs in relation to overhead line components.

In the past decades, there have been many research and development studies on various civil engineering applications dealing with composite materials around the world. Presently, recent research has been carried out on the usage of GFRP angle sections in tower panel, composite CA in a tower, full-scale 66-kV FRP double circuit tower, FRP tower made by filament winding techniques, GFRP triangular base communication tower, GFRP square base tower panel with bolted connection, strength and stability investigations on GFP tower, and carbon fiber–reinforced towers.[19–35]

Articles published so far deal only with the bolted GFRP plate-to-plate connections. Bearing, net tension, shear-out, and cleavage are the four failure modes of a single-bolted FRP plate-to-plate connection under tension loads. Bearing failure is a pseudo-ductile failure that gives audible acoustic emission warning before failures. Other failures such as net tension and cleavage are brittle failures that must be avoided in such connections. By maintaining adequate edge distance "*e*," bolt diameter "*d*," and thickness of width "*w*," shear-out failure can be eliminated. By injecting adhesive into bolted connections (hybrid), the failure can be reduced, and connection performance can be improved. But no research work has been carried out so far on GFRP structural angle member connections with hybrid joints. The novelty of the study is examining the behavior of hybrid joints in plate-to-plate and angle-to-plate connection with e/d ratio is 5. The good performing hybrid joint has been applied in the GFRP tower model and tested under lateral loading for evaluating the effectiveness of such joints.

Materials and Methods

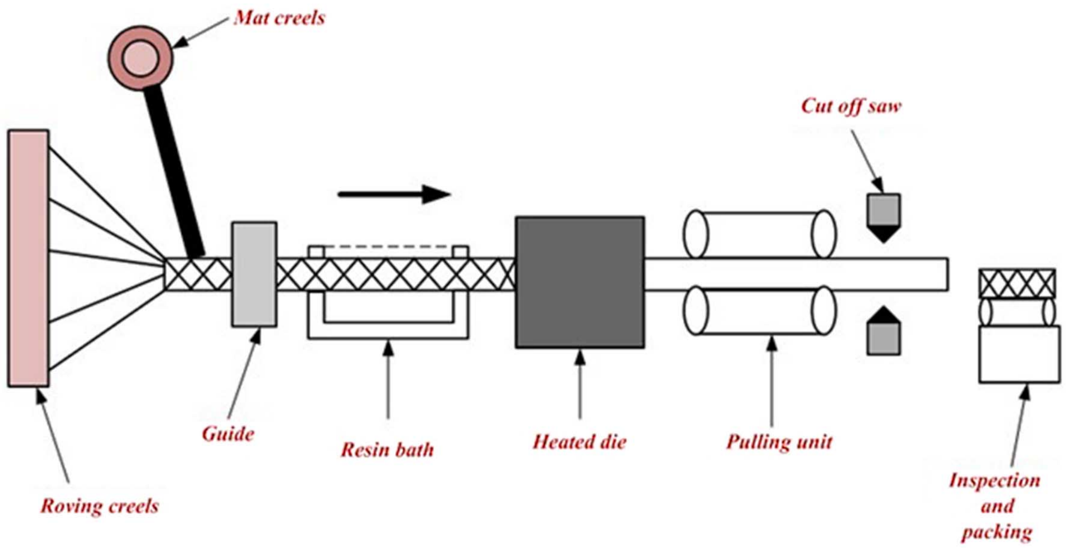
This section includes the GFRP material characteristics and pultrusion process as shown in **figure 1**, and they are used to manufacture the GFRP pultruded angle section. Also, the materials used and test methods such as compression and tensile test are discussed.

MATERIAL CHARACTERISTICS

GFRP was made up of E-glass fiber, polymer matrix, epoxy resin and hardener.[25] In the construction industry, glass/aramid/carbon fibers together with polyester/vinyelster/epoxy resins (polymer) are used in order to form the composite. If glass fibers and polyester/epoxy resins are formed into a composite material, it is called GFRP in the industry.

The pultruded GFRP plates and angles are procured from Meena Glass-fiber Industries, Puducherry, India. The size of the GFRP pultruded angle specimen is 50 × 50 × 6 mm. The material structure consists of alternating layers of unidirectional (pultrusion direction) E-glass fibers, bidirectional woven roving mats are used for the angles, and

FIG. 1 Schematic diagram of pultrusion process.



randomly oriented E-glass continuous strand mats is used. Both sections are provided with an isophthalic polyester resin/matrix. The thickness of the gusset plate and angle profile is kept constant at 6 mm for all connections.

COMPRESSIVE TESTING

By using the same setup, the performance of compressive testing is same as tensile testing. The gripping jaws are reallocated by anvils, and the crosshead pushes toward the stationary grip as compared with pulling away.[35] The compressive testing is commonly done on thick pads with more limited strain as compared with dog-bone specimens, and it is used to predict sufficient functioning over the time period and continuous usage. The three compression coupons are tested as per ASTM D695 standard, *Standard Test Method for Compressive Properties of Rigid Plastics* (Superseded),[36] and results are presented in the **Table 1**. The failure loads are observed for all these three specimens. The compression coupon test, which cuts from GFRP 50 × 50 × 6 mm, is represented in **figure 2*A***.

TENSILE TESTING

Tensile testing is used to employ the mechanical properties of materials, and in a typical tensile test setup, one end of the test samples is clamped with the stationary grip, and the other end is exposed to regulate displacement. In this test, the samples are placed in the shape of "dumbbell" or "dog bone," which cut from films, stamped from thicker samples, or injection molded. The samples are located among the grips and then stretched in the pre-determined rate.[34] According to the displacement (δ), the load is determined by the load cell linked at the moving end. This procedure is proceeded either with predefined displacement or until the specimen breaks. Thus, the stress (σ) and strain ($\in$) is calculated as

TABLE 1
Compression test result

Section	Size, mm	Length, mm	Maximum Crush Value	Maximum Compressive Stress, MPa
Angle	50 × 50 × 6	500	51	450

$$\sigma = \frac{F}{A} \quad \text{and} \quad \in = \frac{\delta}{L} \tag{1}$$

where the normal stress in the plane perpendicular to cross-sectional area is represented as σ, the applied load is represented as F, the original cross-sectional area is denoted as A, normal strain in the specimens gage length is mentioned as $\in$, the variation in specimens gage length is defined as ΔL, and the original gage length is

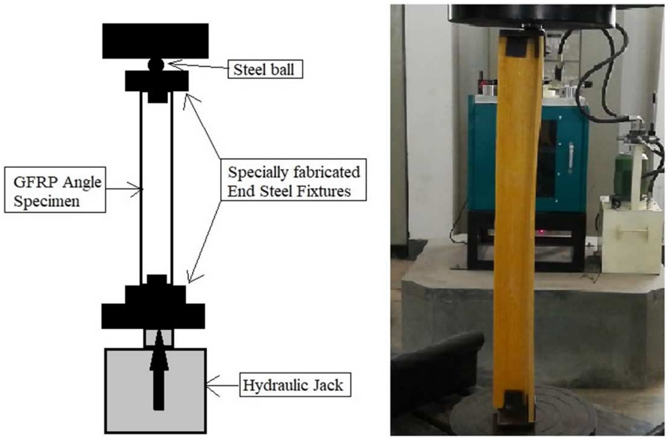
FIG. 2

(*A*) Compression and (*B*) tensile coupon test specimen.

(*A*) (*B*)

FIG. 3

(*A*) Specimen between with end fixtures diagram. (*B*) GFRP angle specimen for compression test.



(*A*) (*B*)

TABLE 2

Tension test result

Section	Size, mm	Maximum Load, kN	Mean Maximum Load, kN
Plate	6	32.480	36.60
		35.310	
		33.820	
		44.880	

denoted as *L*. In this test, there are three dog-bone-shaped samples are considered as shown in **figure 3**, and they are cut for the tensile test as per ASTM standard D3039, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials* (Superseded),[37] to obtain the tensile strength. The tensile properties of GFRP angle sections are measured. The tensile coupon test, which is cut from GFRP 50 × 50 × 6 mm, is represented in **figure 2*B***, and the mean maximum tensile load result of the specimen is presented in **Table 2**.

Experimental Setup

COMPRESSION TEST ON GFRP PULTRUDED ANGLE MEMBER

For the purpose of testing the single-lap joint and butt joint for both single and multiple bolt configurations, specialized testing end fixtures are constructed. The test specimen is placed between the end fixtures as shown in **figure 3*A***, and **figure 4*A*** shows the line diagram of the connected test specimen for compression test. Compression tests are performed according to ASTM D695 to evaluate the behavior of the GFRP angle member used in leg member when it is subjected to compressive load as shown in **figure 3*B***, and **figure 4*B*** shows the connected GFRP angle specimen for compression test.

Preparation of Connected Test Specimen

To investigate the crushing performance of the GFRP pultruded angle member with various connections, a total of 42 specimens of GFRP pultruded angle sections with different combinations of joints, such as butt and lap joints, with different connections, such as bolted, adhesive, and hybrid (bolted + adhesive), are prepared. The specimens are connected by adhesive (epoxy resin), 8-mm-diameter anticorrosive steel bolts and nuts. The mean specimen size is 50 × 50 × 6 mm and 500 mm in height. The edge distance *e* is 40 mm, diameter of the bolt *d* is 8 mm and (*e*/*d*) ratio is 5 are considered for this investigation, and the spacing of bolt to bolt is 20 mm. The thickness of the member and gusset plate is 6 mm. The aim of the compression test is to investigate the crushing performance of the GFRP angle specimen connected with various joints. For the present investigations, four configurations (two-bolted, three-bolted, four-bolted, and adhesive connections) are selected. These connections consist of lap joint, butt joint, hybrid lap joint, and hybrid butt joint.

In this case of two-bolt, three-bolt, and four-bolt connections, four joints (lap joint, butt joint, hybrid lap joint, and hybrid butt joint) are selected, and in the case of adhesive connection, two joints (lap joint and butt joint) are selected to study the behavior for a 50 × 50 × 6 mm leg member. Three specimens are prepared for each joint case. A total of 42 specimens are prepared with edge distance *e* as 40 mm and bolt diameter *d* as 8 mm as shown in **figure 5**.

FIG. 4

(*A*) Line diagram of connected GFRP angle-to-angle specimen. (*B*) Connected GFRP angle specimen for compression test.

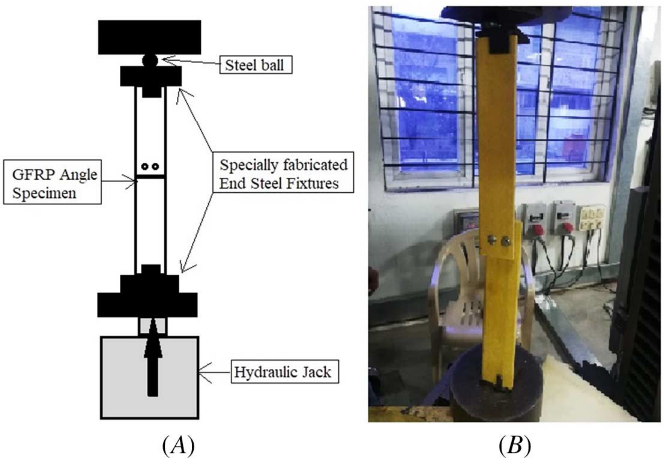
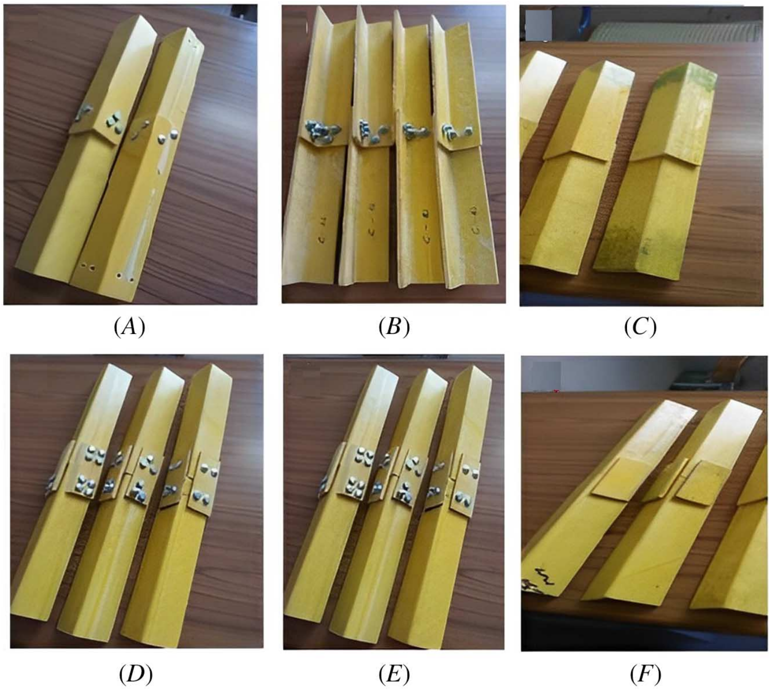


FIG. 5

Connected GFRP angle specimen for compression test: (*A*) lap joint, (*B*) hybrid lap joint, (*C*) adhesive lap joint, (*D*) butt joint, (*E*) hybrid butt joint, and (*F*) adhesive butt joint.



TENSION TEST ON GFRP PULTRUDED ANGLE MEMBER

The angle-to-angle connection of the specimen was cut to the dimension of 240 × 40 × 6 mm as per the codes of ASTM D3039. The specimen was cutting by use of a cutting machine, and the edges were ground by using the grinding machine. The center line of the specimen was marked, and the edge distance is 40 mm, based on an *e*/*d* ratio of 5. Fifteen specimens were prepared for the test. Fifteen set of specimens were divided, and three types of connections as shown in **figure 6** were prepared by testing the tensile test that types were

- Angle-to-angle bolt connection,
- Angle-to-angle hybrid connection (local glue), and
- Angle-to-angle hybrid connection (epoxy).

Bolt Connection

Five sets of specimens with bolted connections in GFRP pultruded angle specimens were prepared as shown in **figure 6*A*** and mark the center line of the specimen and maintain the edge distance of 40 mm and make holes to the marked area and to connect the using of 8-mm bolts, nuts, and washers.

Hybrid Connection (Local Glue)

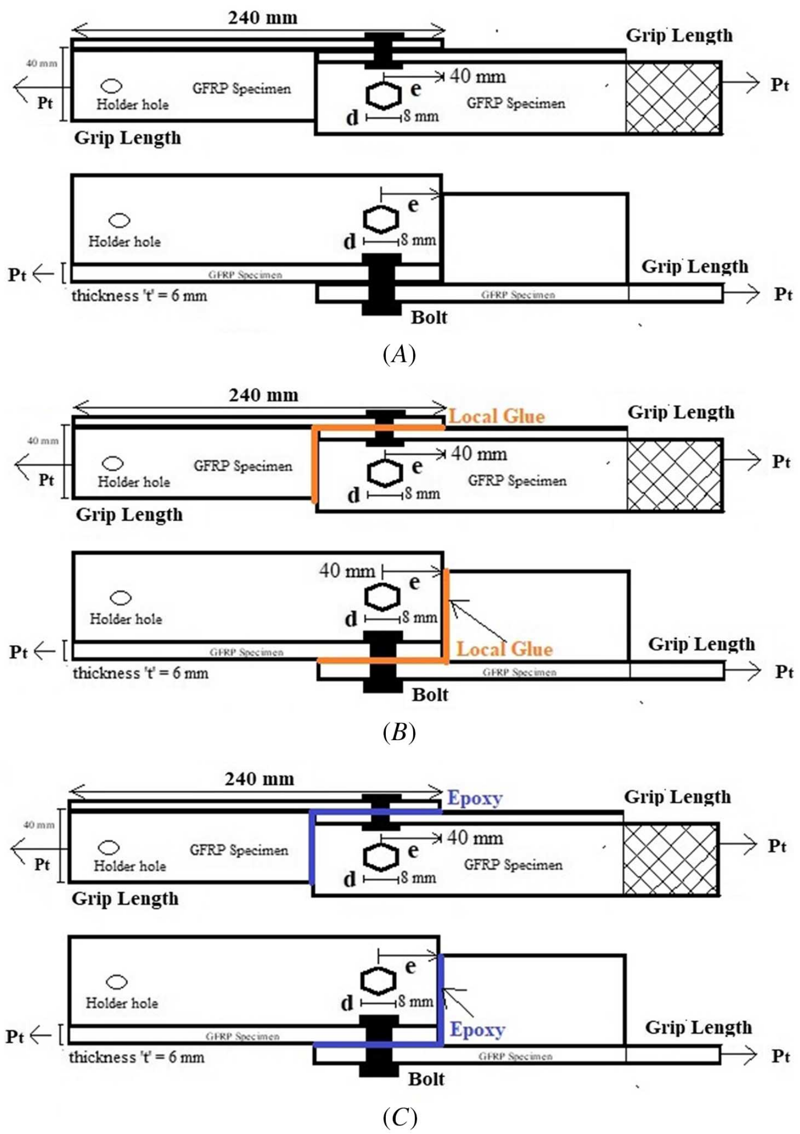
The angle member is connected with bolted connection and local glue, which is the mixture of Flex Kwik and baking soda as shown in **figure 6*B***. The center line in all five specimens was marked and holes were made at 40 mm distance from the edge of the plate. A hole of 8 mm was made in the marked space, after which scratches were made in alternative sides of the plates to make a bonding to the Flex Kwik and the specimen. Some amount of baking soda was also added to the top of the specimen. After the 8-mm bolts, nuts and washers are fixed and tightened.

Hybrid Connection (Epoxy)

The angle member is connected with bolted connection and epoxy resin between the two plates for the set of five specimens as shown in **figure 6*C***. The ratio of the epoxy resin and hardener is 1 kg of epoxy is mixed with 150 mL

FIG. 6

Angle-to-angle connection: (*A*) bolt connection, (*B*) hybrid (local glue) connection, and (*C*) hybrid (epoxy) connection.



of hardener, and it will be fully mixed. The epoxy resin is applied between the connected two plates sections, and the bolt is tightened again.

Result and Discussion

CRUSHING PERFORMANCE

The crushing performance of GFRP angle-to-angle connections for two-bolt, three-bolt, four-bolt, and adhesive connections are given in Tables 3–6, respectively. The ultimate compressive stress for each connection and corresponding displacement has been investigated.

From the test results of the experiments conducted, it is found that the minimum crushing stress is 37 MPa for lap joints and the maximum crushing stress is 615 MPa for hybrid butt joints. Four types of connections

TABLE 3
Experimental test result for two-bolt connections

Serial Number	Joint Name	Angle Specimen, mm	*e*/*d* Ratio	Ultimate Compressive Stress	Displacement, mm
1	Butt joint_1	50 × 50 × 6	5	381	73
2	Butt joint_2	50 × 50 × 6	5		
3	Butt joint_3	50 × 50 × 6	5		
4	Hybrid butt joint_1	50 × 50 × 6	5	583	82
5	Hybrid butt joint_2	50 × 50 × 6	5		
6	Hybrid butt joint_3	50 × 50 × 6	5		
7	Lap joint_1	50 × 50 × 6	5	297	90
8	Lap joint_2	50 × 50 × 6	5		
9	Lap joint_3	50 × 50 × 6	5		
10	Hybrid lap joint_1	50 × 50 × 6	5	556	44
11	Hybrid lap joint_2	50 × 50 × 6	5		
12	Hybrid lap joint_3	50 × 50 × 6	5		

TABLE 4
Experimental test result for three-bolt connections

Serial Number	Joint Name	Angle Specimen, mm	*e*/*d* Ratio	Ultimate Compressive Stress	Displacement, mm
1	Butt joint_1	50 × 50 × 6	5	556	146
2	Butt joint_2	50 × 50 × 6	5		
3	Butt joint_3	50 × 50 × 6	5		
4	Hybrid butt joint_1	50 × 50 × 6	5	615	64
5	Hybrid butt joint_2	50 × 50 × 6	5		
6	Hybrid butt joint_3	50 × 50 × 6	5		
7	Lap joint_1	50 × 50 × 6	5	459	89
8	Lap joint_2	50 × 50 × 6	5		
9	Lap joint_3	50 × 50 × 6	5		
10	Hybrid lap joint_1	50 × 50 × 6	5	516	51
11	Hybrid lap joint_2	50 × 50 × 6	5		
12	Hybrid lap joint_3	50 × 50 × 6	5		

TABLE 5
Experimental test result for four-bolt connections

Serial Number	Joint Name	Angle Specimen, mm	*e*/*d* Ratio	Ultimate Compressive Stress	Displacement, mm
1	Butt joint_1	50 × 50 × 6	5	240	68
2	Butt joint_2	50 × 50 × 6	5		
3	Butt joint_3	50 × 50 × 6	5		
4	Hybrid butt joint_1	50 × 50 × 6	5	411	53
5	Hybrid butt joint_2	50 × 50 × 6	5		
6	Hybrid butt joint_3	50 × 50 × 6	5		
7	Lap joint_1	50 × 50 × 6	5	426	85
8	Lap joint_2	50 × 50 × 6	5		
9	Lap joint_3	50 × 50 × 6	5		
10	Hybrid lap joint_1	50 × 50 × 6	5	79	70
11	Hybrid lap joint_2	50 × 50 × 6	5		
12	Hybrid lap joint_3	50 × 50 × 6	5		

TABLE 6
Experimental test result for adhesive connections

Serial Number	Joint Name	Angle Specimen, mm	*e*/*d* Ratio	Ultimate Compressive Stress	Displacement, mm
1	Butt joint_1	50 × 50 × 6	5	604	60
2	Butt joint_2	50 × 50 × 6	5		
3	Butt joint_3	50 × 50 × 6	5		
4	Lap joint_1	50 × 50 × 6	5	37	8
5	Lap joint_2	50 × 50 × 6	5		
6	Lap joint_3	50 × 50 × 6	5		

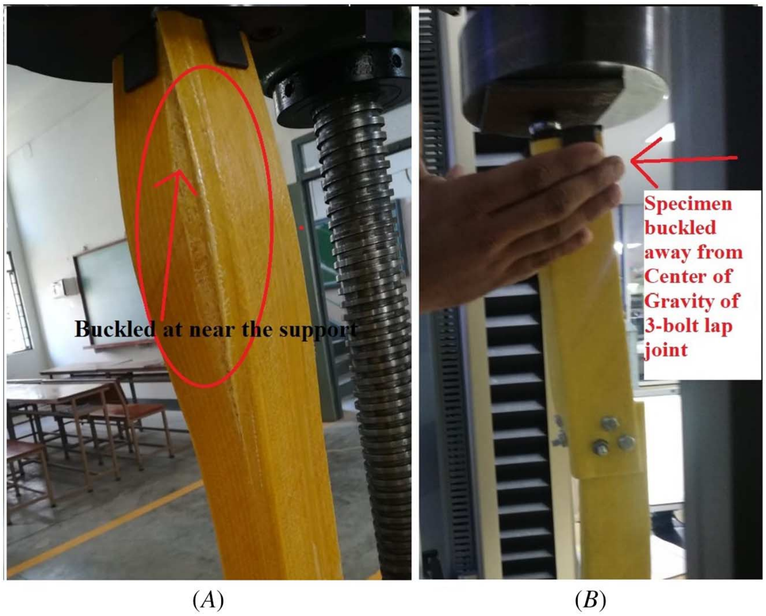


FIG. 7 Buckling failure modes under compression: (*A*) buckled away from center of gravity of specimen and (*B*) buckled at near the support.

(two-bolt, three-bolt, four-bolt, and adhesive) with four types of joints (butt joint, lap joint, hybrid butt joint, and hybrid lap joint) have been prepared for this study. In each combination, three specimens were prepared and tested for load-displacement behavior. The specimen fails at end of the support for GFRP angle section without connection, and the fiber is fractured at the end of flange portion as shown in figure 7*A*. The specimen of two-bolt, three-bolt lap joint GFRP angle with connection buckled away from the center of gravity specimen as shown in figure 7*B*. The specimen of four-bolt connection fails due to crushing at the bolt holes because of discontinuity of the fibers.

TENSILE PERFORMANCE

From the review of literature,[16] it is reported that there are four common failure modes, 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 8–10. The tensile performance of GFRP angle-to-angle connection test results are presented in Table 7.

The experimental results show that the failure loads increase when adding adhesive (epoxy) along with bolt connection. An increase of about 8.2 % was observed. The elongation at peak load exhibited an increase of about 45.2 % for *e*/*d* ratio 5 in the angle-to-angle connections.

FIG. 8

Angle-to-angle bolt connection tested specimens.

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

LATERAL LOAD TEST ON DIAGONAL BRACED GFRP TOWER

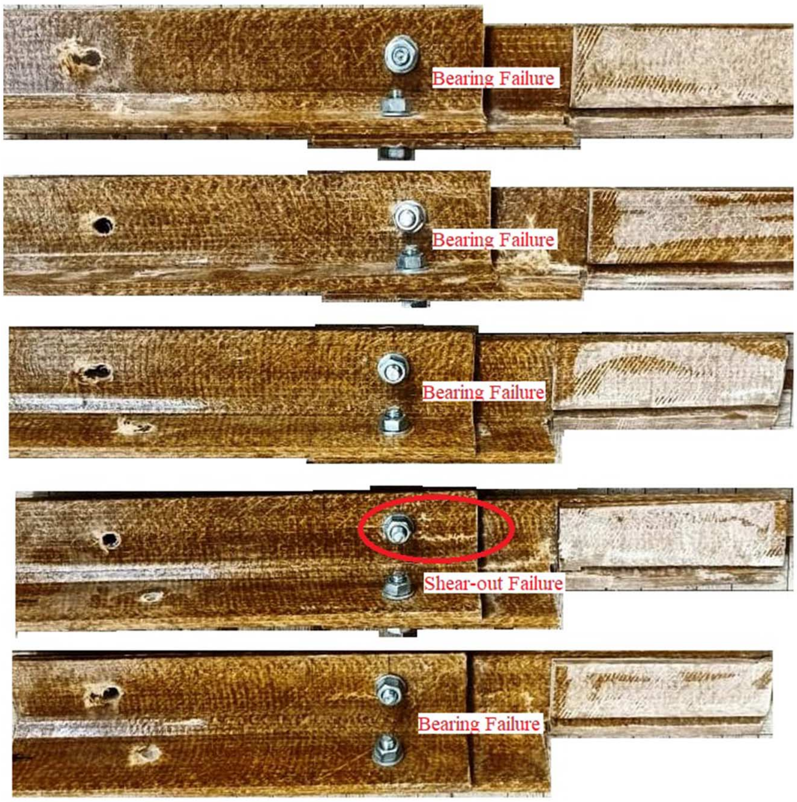
The performance of transmission line tower under lateral loading condition is explained using the numerical investigation and through experimental analysis is discussed in this section. Here, the maximum deflection of steel and GFRP transmission line tower models are evaluated to find the performance.

Analytical Investigation

In this research, the FE simulation modeling process was used to initialize the structural analysis, and it represents the real conditions of the experiment. The mechanical properties of GFRP composite tower angle were considered as an input for the FE simulation. Once the size and dimension of GFRP composite tower angles are decided, then they are given to the structural analysis. According to the fundamental of laminated composite modeling, the inputs are upgraded in the setting of computational simulation. Generally, numerical analysis of investigation is performed in a commercially available computer program, ANSYS, using the FE models of test specimens obtained. The connection geometries used in FE are considered as same as those utilized experimental portion of the

FIG. 9

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



study. The multilinear stress–strain relation along with Von Mises yield criteria is used to specify material behavior in angles. An extra effort is needed to model different component accurately.

FE Analysis of 18-m Transmission Line Tower

The transmission line tower model is modeled in STAAD Pro as three-dimensional truss models. The base of tower line (TL) is 3 m, and the height of TL is 18 m. The tower leg is fixed with support. For analysis purpose, the vertical leg angle sections of TL is considered as the most load-bearing member. The leg member section was 100 × 100 × 6 mm and was immersed in the concrete base. This provided constrain in every direction. As the diagonal bracing angle sections, horizontal bracing angle sections and angle sections in cross-arms are low load-bearing , 50 × 50 × 6 mm angle section were used. For FE Analysis, conductor was considered as the steel-reinforced aluminum conductor. The bolt, adhesive, and hybrid connections are connected with GFRP angled angle sections eccentrically. The gusset plate is 100 × 200 × 6 mm. The steel-reinforced aluminum conductor is taken as appropriate conductors, like steel-cored aluminum strand wire cables.

Load Details on Transmission Line Tower

Wind load is an important vital load that acts on transmission towers. As per IS 875 (Part 3)–1987, *Code of Practice for Design Loads (Other than Earthquake) for Buildings and Structures: Part 3 Wind Loads*, the design wind pressure by guest load method has been estimated, and it is found to be 609.035 N/m^2. The estimation of wind force along the wind direction on the structure is found to be 43.54 kN. The estimation of wind load on conductors is 7.1 kN, which is transmitted to point loads and applied in GFRP method. The estimation of wind load on the ground wire is 8.56 kN, which is transformed to point load and applied at the tip of tower model. The

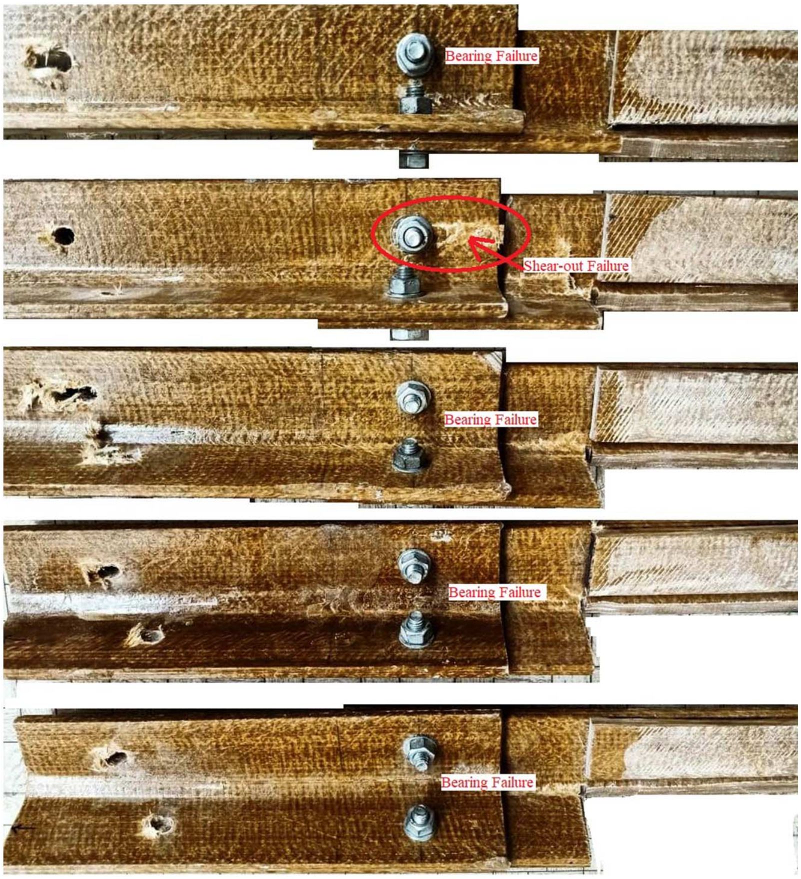


FIG. 10
Angle-to-angle hybrid connection (epoxy) tested specimen.

TABLE 7
GFRP Angle-to-angle connection tension test results

Section	Specimen ID	*e*/*d* Ratio	Failure Load, kN	Mean Failure Load, kN	Elongation at Peak	Average Elongation at Peak	Failure Mode
Angle-to-angle bolt connection	AB1	5	32.270	31.26	10.65	6.08	Bearing failure
	AB2	5	25.880		1.590		Bearing failure
	AB3	5	34.490		1.660		Bearing failure
	AB4	5	31.490		9.160		Bearing failure
	AB5	5	32.190		7.360		Bearing failure
Angle-to-angle hybrid (local glue) connection	AG1	5	34.030	32.41	10.14	7.53	Bearing failure
	AG2	5	31.880		8.950		Shear-out failure
	AG3	5	33.240		9.430		Bearing failure
	AG4	5	31.200		6.020		Bearing failure
	AG5	5	33.190		3.130		Bearing failure
Angle-to-angle hybrid (epoxy) connection	AE1	5	34.110	33.83	7.010	8.83	Bearing failure
	AE2	5	34.100		10.630		Bearing failure
	AE3	5	34.880		9.300		Bearing failure
	AE4	5	33.460		9.210		Shear-out failure
	AE5	5	32.580		8.010		Bearing failure

TABLE 8
Load calculation details

Serial Number	Description	Value
1	Wind force along the wind direction on the structure	43.54 kN
2	Wind load on conductor	7.1 kN
3	Wind load on the ground wire	8.56 kN
4	Self-weight of the tower, including conductor, insulator, repairing line man, and all other accessories etc., from FE analysis	5.69 kN (GFRP tower) 17.74 kN (Steel tower)

vertical load contains weights of insulators, conductors, towers; repairing line man and every other accessory are all involved in transmission towers. The wind loads at the body of tower is to the suitable intensity STAAD pro model. The detailed load calculation is furnished in Table 8.

FE Analysis of Steel Tower with Bolt Connection

In this case, steel is used as a material for the transmission tower, and bolts are modeled as joints in the model during element formulation. Maximum deflection of steel tower with bolt connection is displayed in figure 11, and it is 67.22 mm due to the wind load along with the specified loads on the side.

FE Analysis of GFRP Tower with Bolt Connection

The maximum deflection of GFRP transmission line tower with bolt connection, as shown in figure 12, is 54.55 mm because of the wind load along with the specified loads on the side.

FE Analysis of GFRP Tower with Adhesive Connection

Epoxy (adhesive) is modeled as bonded contact throughout the tower in FE modeling. Figure 13 represents the maximum deflection of GFRP transmission line tower with adhesive connection.

FIG. 11 Deflection of 18-m steel tower with bolt connection.

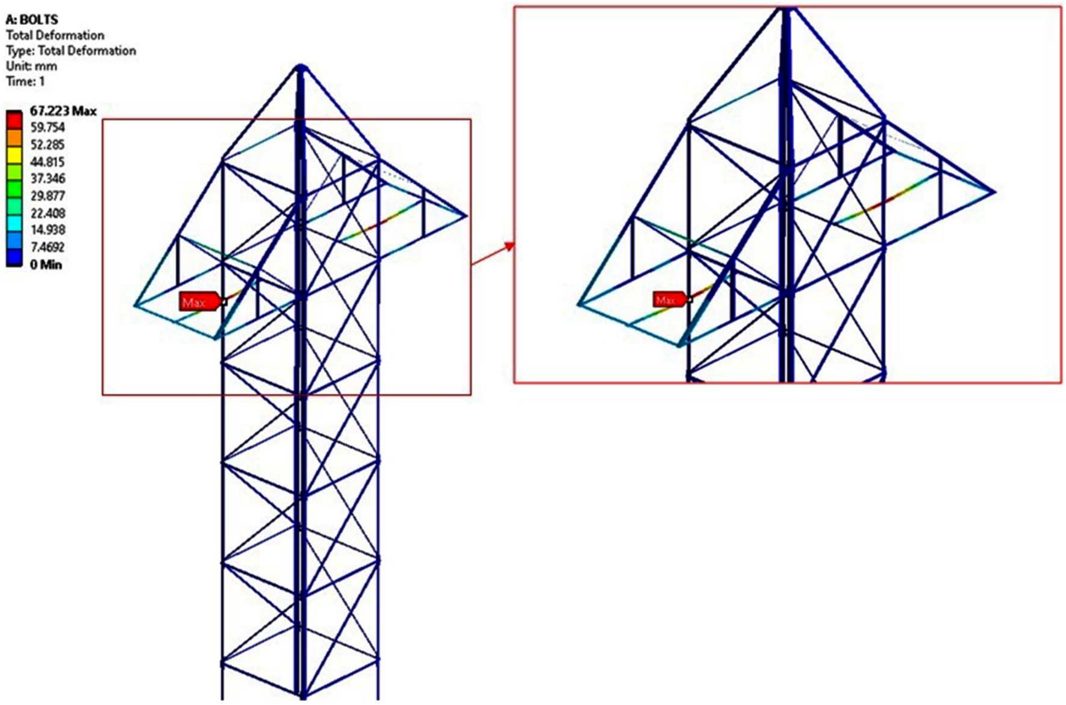


FIG. 12 Deflection of GFRP transmission line tower with bolt connection.

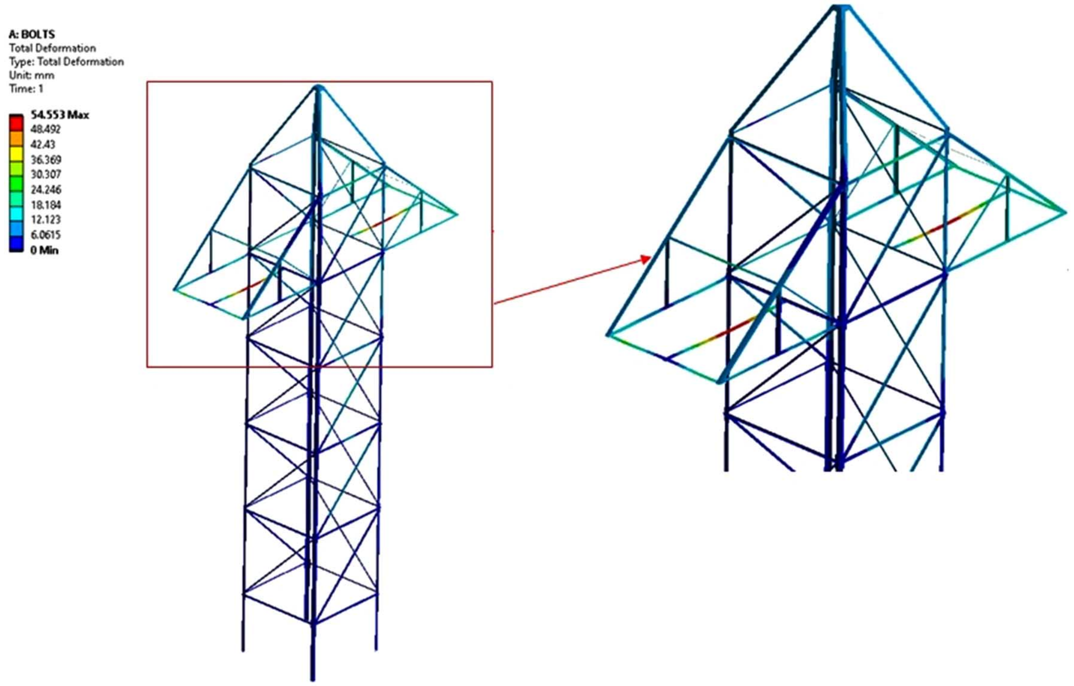


FIG. 13 Deflection of GFRP transmission line tower with adhesive connection.

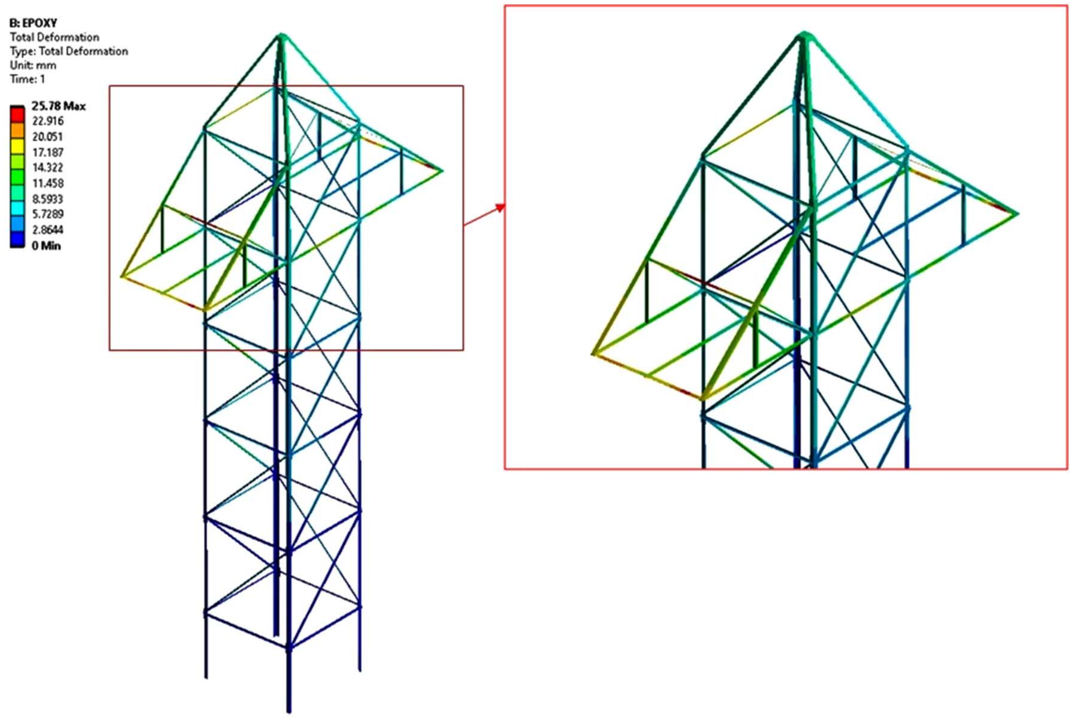


FIG. 14 Deflection of GFRP transmission line tower with hybrid connection.

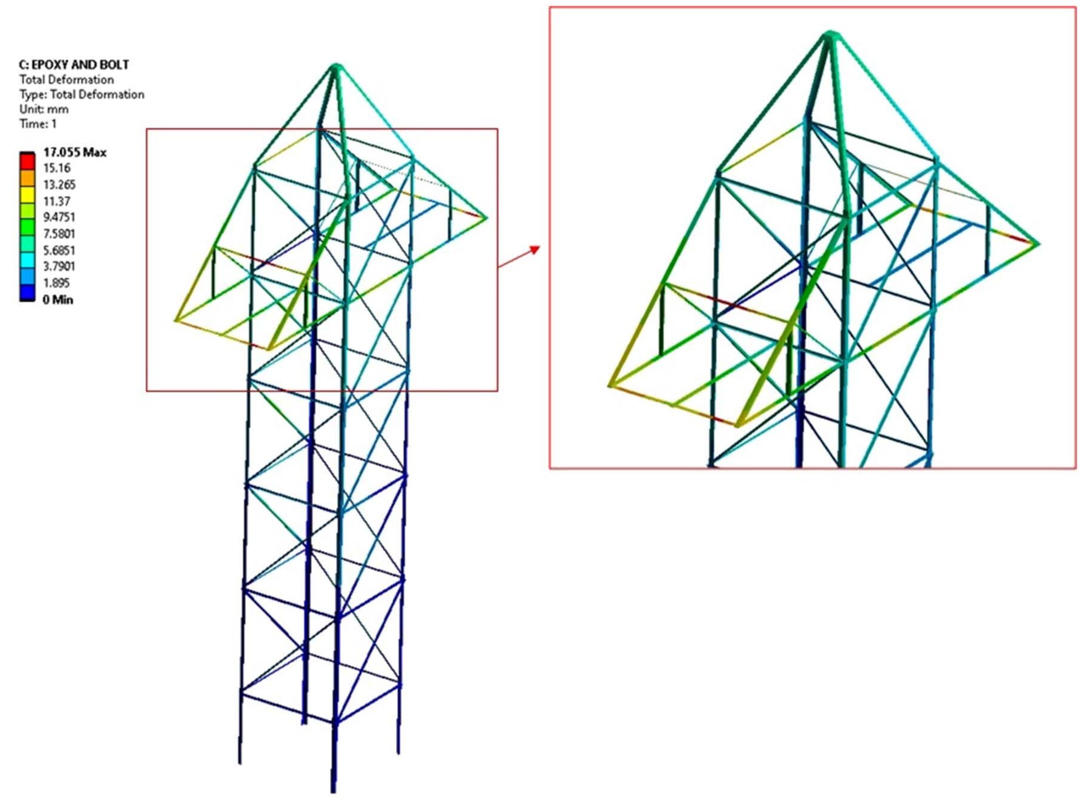


TABLE 9
FE analysis results comparison

FE Analysis Result	Steel Tower 18-m Model with Bolted Connection	GFRP Tower 18-m Model		
		Bolted Connection	Adhesive Connection	Hybrid Connection
Maximum lateral deflection (mm)	62.22	54.55	25.78	17.05

FE Analysis of GFRP Tower with Hybrid Connection

Epoxy (adhesive) is modeled as bonded contact throughout the tower. Bolts are modeled as joints in FE modeling. Figure 14 illustrates the maximum deflection of GFRP transmission line tower with hybrid connection and is 17.05 mm because of the wind load along with specified loads on the side.

From the Table 9, the maximum deflection of the tower at the top for steel tower, GFRP tower with bolt connection, adhesive connection, and hybrid connection have been found to be more for steel tower and less for GFRP tower with hybrid connection, which is less than 1 % of height of the tower. According to Bhowik, Gupta, and Chakraborti[6] and Selvaraj, Kulkarni, and Rameshbabu,[10] the deflection of the tower under normal condition and broken wire conditions should be less than 1 % of height of the tower. In this study, the maximum deflections of all cases of towers were validated that comes under safe limit from reported in the literature. The GFRP tower with hybrid connection has the most effective value among the transmission towers.

Conclusion

Based on the experimental and numerical investigations, the following are the main conclusions.

- The specimens of built-up GFRP angle sections under axial compression buckled at mid portion of the specimen and also the specimen returned to original position while unloading.
- Based on the experimental study, it is observed that two-bolt hybrid lap joint connection exhibited an increase in compressive stress and decrease in deflection.
- The influence of hybrid connection for GFRP angle member under compression increase the stress withstanding capacity and decrease the deformation. Hence, it can improve the stability of the compression angle sections.
- Two different modes of failure are observed during experiments, bearing and edge shear-out failure.
- In the angle-to-angle member with bolt connection, all the specimens exhibited shear-out failure and bearing failure mode. In the hybrid (local glue) connection, one specimen exhibited shear-out failure, and four specimens exhibited bearing failure. In the hybrid (epoxy) connection, all the five specimens exhibited bearing failure.
- Among the angle-to-angle connections, the hybrid (epoxy) connection withstood more strength capacity.
- The performance evaluation of GFRP transmission line tower with various connections, such as bolt, adhesive, and hybrid connection, has been done using ANSYS software, and the deflection behavior under lateral load conditions was compared with steel transmission line tower.
- The GFRP transmission line tower with hybrid connection is able to perform with maximum efficiency among all other connections. Hence, hybrid connections can be suggested to use in transmission line tower structures.

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