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Crushing performance of pultruded GFRP angle section with various connections and joints on lattice towers

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ABSTRACT

The significant features of the GFRP angle make it one of the modern construction members for the present lattice-type Transmission Line Towers (TLT) made out of mild steel. The GFRP structural angle members with gusset plate connections for net-crushing strength are investigated in this study, with an emphasis on connections to transmission line towers. Forty-two specimens of single-lap, butt joints with bolted connections are considered in this study. The gusset plate and edge distance have different widths. The joint is subjected to a compression load before failure modes and the associated loads were noticed. An experimental investigation on the crushing behaviour of GFRP angle sections to determine the crushing performance against the standard crushing force of different connections such as bolted, adhesive, and hybrid (bolted + adhesive) with various joints (butt and lap) has been carried out and are presented. Additionally, the impact of plate edge distance and width on connection effectiveness is investigated. The innovation of the work is in the evaluation of the crushing value for bolted GFRP structural angle members of 2, 3, and 4 nos with gusset plate connections that have been used to predict the compressive strength.

Keywords: Angle section; Connections; GFRP; Pultrusion; Transmission Line Tower (TLT).

1. INTRODUCTION

Glass fiber reinforced polymer (GFRP) possesses significant characteristics such as being light weight, corrosion resistant, non-conductive, environmentally friendly, high tensile strength, low moisture absorption capacity and good life cycle [1, 4–8]. As such these materials are very much used in aerospace, military, shipping, car, construction industries, sports and recreation, marine, and energy sectors [9, 10]. While some articles dealing with the buckling characteristics of GFRP have been published, papers dealing with the crushing behaviour of GFRP angle sections and studies on the connection's behaviour of lattice tower members made up of GFRP are very scarce [11]. Attempts to use GFRP materials in Transmission line towers (TLT) have also been in trend in many western countries such as USA, China, Russia, Canada, and European Union. GFRP materials are rapidly being considered for the fabrication of cross arms and poles throughout the utility industry in these countries considering the optimized balance of economic and engineering considerations. But this trend is a research stage only in India [12-13].

On reviewing the literature dealing with the behaviour of GFRP members of various shapes, buckling behaviour, connection behaviour and failure studies in TLT, it is observed that CIGRE working group technical brochure [14] has suggested future research on the evaluation of the structural strength of Fibre-Reinforced plastics (FRP) based on coupon test, improvising the development of bolted joint design for lightweight structures from FRP pultruded materials and connection behaviour in the lattice members [15–17]. In the building of transmission line towers, gusset plates are common materials that are often used for connecting the structural angle members. In the 1970s, studies on concentrically loaded GFRP bolted connections began [18–21]. Experimental investigations on single-bolted, single/double plate-to-plate connections for static tensile loads have been carried out by MOTTRAM and TURVEY (2003), COOPER and TURVEY (1995), [22–23]. Experimental studies on the behaviour of multi-bolted single/double lap plate-to-plate connections have been

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conducted by PRABHAKARAN and ROBERTSON (1998), PRABHAKARAN *et al*., (1996), MOTTRAM (2010), HASSAN *et al*., (1997) and PARK *et al*., (2009) [24–27]. The study is to investigate the mechanism of failures of single-bolt and multi-bolted connections in tension. A direct semi-empirical analytical method considering the stress-concentrated issue has been found by HART-SMITH (1978) [28] and ROSNER [29]. Researchers, such as ROSNER and RIZKALLAL (1995) [30] have proposed a logical method to forecast the strength of single/multi-bolted connections for the net-tension strength using the mentioned idea. To the authors' knowledge, there is no published research on the relationships between GFRP structural angle members and GFRP gusset plates [31–33]. The experiments on GFRP plate-to-plate contacts, however, have been published by numerous researchers, as was indicated above [34–36]. For GFRP single-bolted connections, it has been noted that there are four primary joint failure modes: edge-shear out, bearing, net-tension and cleavage modes [37]. It is observed that the edge-to-hole diameter ratio is less than 3, the edge shear-out failure mode occurs more frequently and is more prominent in the angle section, which is more susceptible than the plate section due to its different material structure [38]. A sufficient edge distance can completely prevent the edge-shear-out form of failure. A standard equation for calculating failure loads under cleavage/bearing has been suggested by (HASSAN *et al*., 1997) [39] since the cleavage mode is categorized as a sort of bearing failure, the bearing failure mode equation can be modified suitably. Due to the heterogeneity, anisotropy, brittle nature, high-stress concentration, and nonlinear behaviour of GFRP, the current steel conventional equation cannot be used to predict net-tension failure. To account for these elements, the traditional equation needs to be adjusted [40–46].

An alternate methodology to compute shear strength and shear modulus of pultruded Glass FRP materials from the stress-strain curve and load-displacement data based on regression analysis and experimental investigations has been mentioned by BAKIS *et al*., [47]. Selvaraj [48] has attempted to design and build a prototype TLT made of GFRP and the study reveals that the building of power TLT using GFRP angle sections and proper connection method is possible in India. The failure of FRP pultruded sections is characterized by fiber architecture, as it was more where the content of fiber is low. M.D. RAGHUNATHAN *et al*., has commented about the lack of knowledge on data necessary for the design of GFRP angle connections etc. Hence there is a need for undertaking research activities for generating characteristics data of such members [49]. N. PRASAD RAO *et. al*., observed that the specimens were buckled in out of plane mode and alternatively resulted in crushing and debonding failure [50]. S.Y. KIM *et al*., [51] have investigated four modes of failure such as net-tension, edge shear out, cleavage, and bearing during experiments. D. UNGUREANU *et. al.,* [52] has recommended for investigating the crushing strength of such bonded GFRP members has to be investigated to understand in order to ascertain the feasibility of using GFRP members with proper connections in TLT. It was observed that axial crushing of the composite tubes has better energy absorption than off-axis by JOHANSON [53], friction mechanisms and bending resistance also seem to be affecting the energy absorption capacity of composite tubes. The investigation of static crushing behaviour on filament winding laminated carbon and glass hybrid circular composite shells reveals that energy absorption capacity affected strongly by a sequence of reinforcement exhibited excellent energy absorption capability and stiffness increases with volume reduction decreases [54–56]. The effect of slenderness ratio upon buckling behaviour of GFRP angle section has been investigated and reducing effective length for measuring torsional – flexural buckling made for GFRP angle section with bolted connection has been calculated with an outlined formula [57].

In the reference [58], the major goal is to create simple semi-empirical design guidelines for TLT member connection net-compression failure. Thirty-five connections were put to the test until they failed. To achieve the desired failure modes adjustments have been made in width and edge distance. Loads of failure took place and modes are detected after applying a compressive force to the joint. In the net-tension failure mode, 17 of 42 specimens are failed. These findings were used for further investigation [59]. The composite stress concentration factors are derived using the experimental results. Hart-closed Smith's form solution is used to calculate the elastic isotropic stress concentration factors. The evaluation of the crushing value for bolted GFRP structural angle members with 2, 3 and 4 nos with gusset plate connections have been used to predict the compressive strength based on limited test results, which is the work's novelty.

In the durability point of view [60], as TLT made up of FRP are possessing good performance against corrosion and weathering action etc. This has been used as a proven material however still studies are going on in many countries including India especially corrosion behaviour and many structures have been erected in Western countries and China etc.

From the published literature reviewed, it is noted that the crushing performance of angle specimen made up of pultruded glass fiber-reinforced polymers are not dealt with, with various combinations of joints and connections. As these sections are emerging as one of the promising materials in the innovative design and installations of TLT with GFRP, there is a need for generating more mechanical properties data. Under this ambit, this study is aimed to find out the crushing performance of GFRP angle section with different combinations of joints and connections under crushing load and to identify the best combination among them.

2. MATERIALS AND METHODS

GFRP specimens that are fabricated in a unidirectional fiber orientation using pultrusion techniques as shown in Figure 1 by Meena glass fiber Industries, Puducherry have been procured for experimentation [61-62]. It was manufactured by the pultrusion process as shown in Figure 1. It is made of E-glass, and the polymer matrix used is polyester resin and its hardener. The members are visually inspected and the good members were selected as per ASTM standards [02].

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 as shown in Figure 2. The specimens are connected by adhesive (epoxy resin), 8 mm diameter anticorrosive

Figure 1: A view on fabrications of GFRP angle sections by pultrusion process.

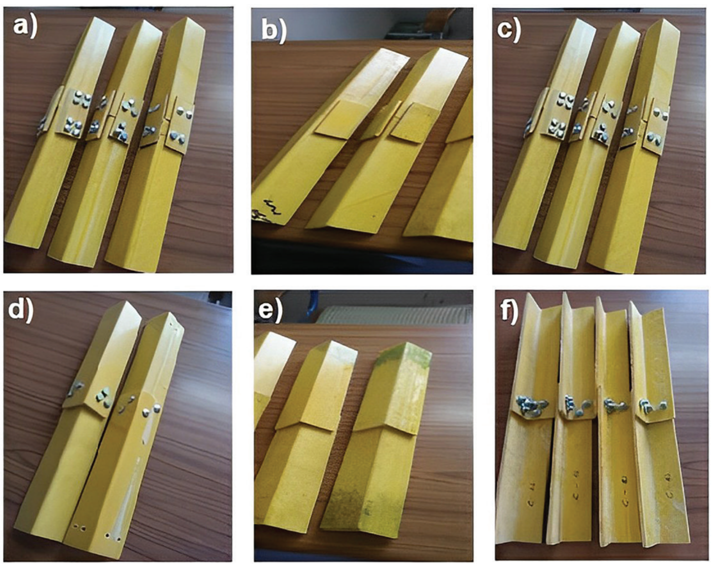

Figure 2: Different combinations of joints and connections of GFRP angle sections a) 2, 3 and 4 bolted butt joint, b) adhesive butt joint, c) hybrid 2, 3 and 4 butt joint, d) 2 and 3 bolted lap joint, e) adhesive lap joint and f) hybrid 2, 3 and 4 lap joint.

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 thick [63].

3. EXPERIMENTAL TEST

3.1. GFRP angle specimen test

GFRP angle specimen of size 50 × 50 × 6 mm is chosen for this experimental investigation based on the availability in the market. The MTS-810 universal testing equipment with 500 kN static and dynamic capacities was used to test these specimens [64]. The grips of UTM were used to hold the coupon specimens. Figure 3 shows the test setup of the GFRP angle section.

The gripped specimen's longitudinal axis is precisely positioned along the test direction. In order to prevent the test specimen from slipping throughout the test, the grip lengths are tightened to a pressure of 5.52 MPa and were between 75 and 80 mm on either side. A constant strain rate with a displacement rate of 2 mm/min has been set up for the test speed in the gauge part. In order to measure strains, two electrical resistance strain gauges were employed in each specimen, one in the middle of the mid-length and the other at the third of the gauge length. These strain gauges have been linked to a data acquisition system logger so that the strains could be recorded throughout the testing process. The UTM data collecting system is also used to collect the measurement data for the loads and strains [65–67]. The data acquisition system provided the displacement reaction, which is then tracked throughout the testing period. Figure 3 depicts the setup for the compression test. Although ASTM standards [03] are followed in the preparation of the specimens, it is found that several examples failed quite close to the grip rather than at the gauge position. Because the standard requires a consistent width for the whole section, the width of the specimen was reduced to 20 mm along the gauge length and then tested for failure, which is why the failure occurred. The 3 compression coupons were tested as per ASTM D695 standard [03]. The maximum compressive stresses were observed for all these three specimens respectively. Table 1 provides a summary of the test outcomes.

GFRP angles of size 50 × 50 × 6 with length of 500 mm exhibited bending slightly at the end of the support and failed specimen returned to its original shape while unloading as depicted in Figure 4(a). The connected GFRP angle specimens with length of 500 mm exhibited bending slightly at the joint and failed specimen returned to its original shape while unloading as depicted in Figure 4(b), but it is observed that bolt got little dislocated. The major mode of failure observed is buckling during the testing of the GFRP angle specimen.

Figure 3: Experiment setup of GFRP angle section for compression test.

Table 1: Maximum compressive stress of GFRP angle sections.

SECTION	SIZE (mm)	SPECIMEN NUMBER	LENGTH (mm)	SLENDERNESS RATIO	MAXIMUM COMPRESSIVE STRESS (MPa)	MEAN MAXIMUM COMPRESSIVE STRESS (MPa)
Angle	50 × 50 × 6	1	500	51	450	451
		2	500	51	436	
		3	500	51	467	

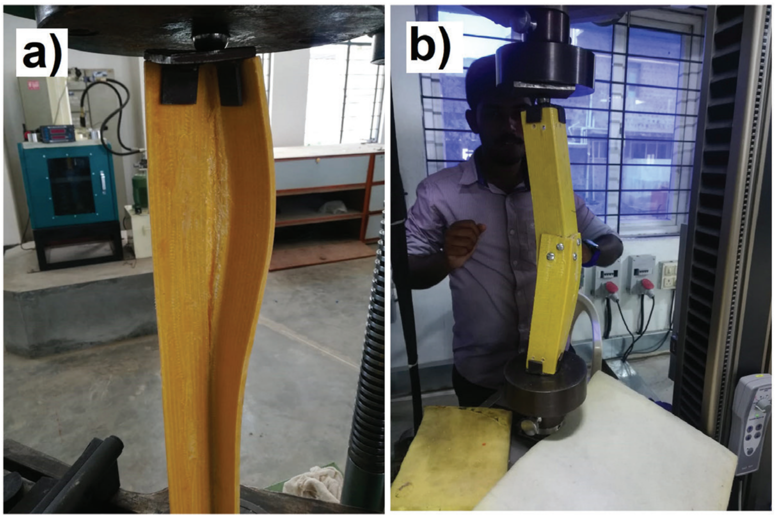

Figure 4: Buckling behaviour of GFRP angle specimen (a) 50 × 50 × 6 mm with length = 0.5 m (b) GFRP angle specimen bolted connection with length = 0.5 m.

3.2. Laboratory configuration

For the purpose of testing the single-lap joint and butt joint for both single and multiple bolt configurations, a specialized all-steel testing apparatus is constructed [68]. A horizontal load frame attached to a hydraulic jack that was specialized electrically with a digital display of load at the loading end is used. The hydraulic jack has a 500 kN capability. To allow compressive loading, a high-tensile-strength steel holder with a capacity of around 500 kN was utilized inside the two beams, with steel fittings at both ends that allowed for a configuration to connect the produced gusset plate and angle section with steel nuts and bolts.

3.3. Specimens for tests: planning and preparation

In order to investigate the behaviour of the connection for low-to-medium voltage transmission line towers, a structural GFRP angle bracing members is identified and selected [69]. Crushing tests are carried out as per ASTM D695 standard [03] using a compression testing machine. These specimens are placed in between the metal holders which held the specimen tightly at both ends underneath the load testing plates. All specimens are subjected to compression at a rate of 1 mm/min. An automatic data acquisition facility has been used in the study for monitoring and recording load-displacement behaviour in a quality testing research laboratories. The tests are conducted on various connected specimens as depicted in Figure 2.

One of them is a bracing component that measured 50 × 50 × 6 mm. The gusset plate and member are retained at a constant thickness. Steel bolts with a 8 mm standard diameter with 1.5 mm hole clearances are typically used in this investigation as used in the reference. The tests main goal was to create design guidelines for junctions between light to medium voltage TLT members using various bolt configurations. Each bolt arrangement will have a single cross-correlation coefficient that may be used to calculate the joint strength for the net-compression failure mode. This coefficient is obtained using a semi-empirical methodology. The test protocol was selected after taking into account the affecting factors, including the bolt diameter (‘d’) and edge distance (‘e’). Three plate widths with three different edge distance values are chosen for each bracing

Figure 5: Experimental setup of GFRP angle sections a) 2 bolted butt joint, b) 3 bolted hybrid butt joint, c) 2 bolted lap joint and d) 3 bolted lap joint.

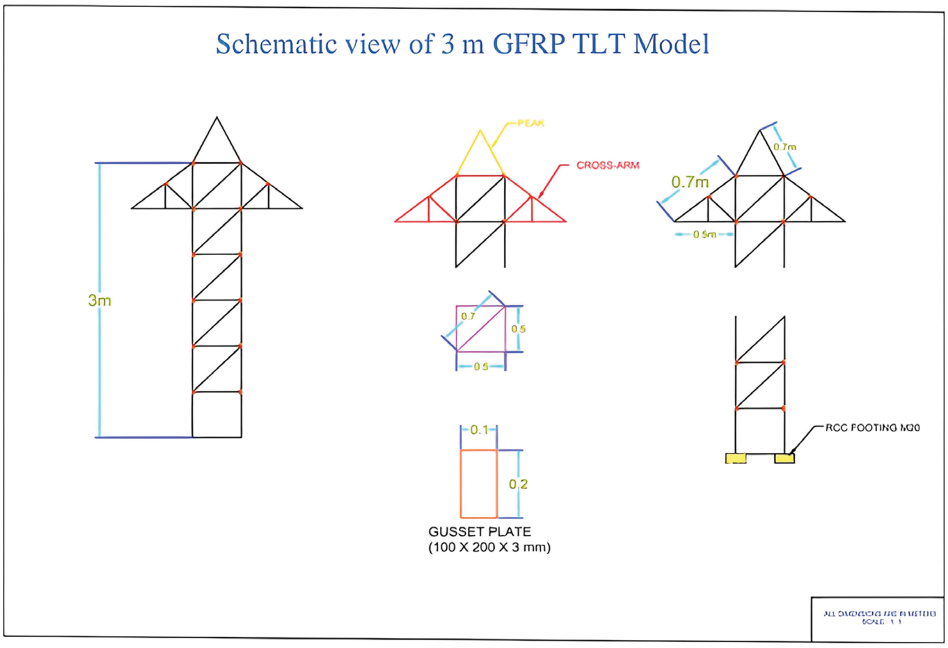

Figure 6: Schematic view of 3 m GFRP TLT model.

member. The schematic in Figure 5 presents the experimental setup of testing GFRP angle pultruded section with different connections. Nine specimens are included in the series, which was created for the angle section member measuring 50 × 50 × 6 mm. The edge distance is 40 mm, while the bolt diameter is maintained at 8 mm which corresponds to e/d ratio of 5 for the edge distance to bolt diameter. Three identical specimens are created for edge distance of 40 mm. The width of the narrow plate will only fail in the net-compression mode, according to the literature. The net-compression failure mode is the main failure mode in the narrow plate width. For this reason, the specimen lengths are chosen so that the joint behaviour would not be impacted by or overlap with the local stresses. The minimum pitch distance to the bolt diameter, or p/d and e/d ratios of 5, were maintained in all circumstances but in the single-bolt scenario. The creation of a typical specimen connection sketch and the appropriate measurements are shown in Figure 2.

3.4. Experimental investigation on GFRP tower with hybrid connection model

A GFRP TLT model with 0.5 m × 0.5 m base and top dimensions and 3.5 m height is chosen for the experimental investigation as followed in the research work. The schematic view of the tower model is shown in Figure 6. For leg bracing, a 50 × 50 × 6 mm GFRP equal angle section was employed. The dimensions of the gusset plate were 100 × 200 × 6 mm. The pitch and edge distance for the leg and bracing member were

Figure 7: Testing on GFRP TLT model with hybrid connection.

kept at 50 mm and 40 mm respectively, to avoid the crushing of fibers between the bolts and edge shear failure. As shown in Figure 7, the tower model is created and placed in the test concrete bed. The bracing components were joined to the leg component using two bolts and GFRP gusset plates. The load is provided by a manually driven screw jack, and the deflection is measured using scale setups.

The following design parameters are used for tower design, as per the reference. Based on the preliminary investigation carried out as a part of the research, as 2 bolt hybrid joint exhibited superior performance when compared to all other joints, the same has been selected for the GFRP tower model study.

Topography factor: 1.0, Risk coefficient: 1.08, Terrain category: 3 and Wind speed: 50 m/s. The design load is chosen to approximate the wind load on top of the tower model. The tower model is subjected to lateral loading. The load is applied in 5 kN increments until the design load of 48 kN is reached at both load sites. The tower model's deflection is measured concurrently using scale setups. The tower model successfully resisted the design load.

3.5. Numerical validation of 3 m GFRP TLT with hybrid connection model by ANSYS

The tower model experienced the maximum forces of design load of the actual tower of 18 m in height. To investigate the maximum capacity of the tower model, the model is modeled in the FE analysis software, ANSYS.

In the finite element analysis, GFRP plates and beams are modeled in SHELL 181. The SHELL modeling technique is employed to maximize the accuracy of the results and to decrease the computational time. Second-order quadrilateral elements with 8 nodes are used to build the finite element model. Joints are used to model the bolts which are quite an effective method in the FE analysis as per ANSYS help guide. Bonded contact is used to model the adhesive paste because after the adhesive the two surfaces will be connected together just like bonded together. ANSYS model is shown in Figure 8.

The colour variation seen in the Ansys software output as shown in the Figure 8 indicates stress concentration difference. The red colour indicates the higher stress concentration near the bolt. This is due to the hole being the vulnerable area for stress concentration. The results (loads vs deflections) obtained through model study using Ansys software is shown in Table 2.

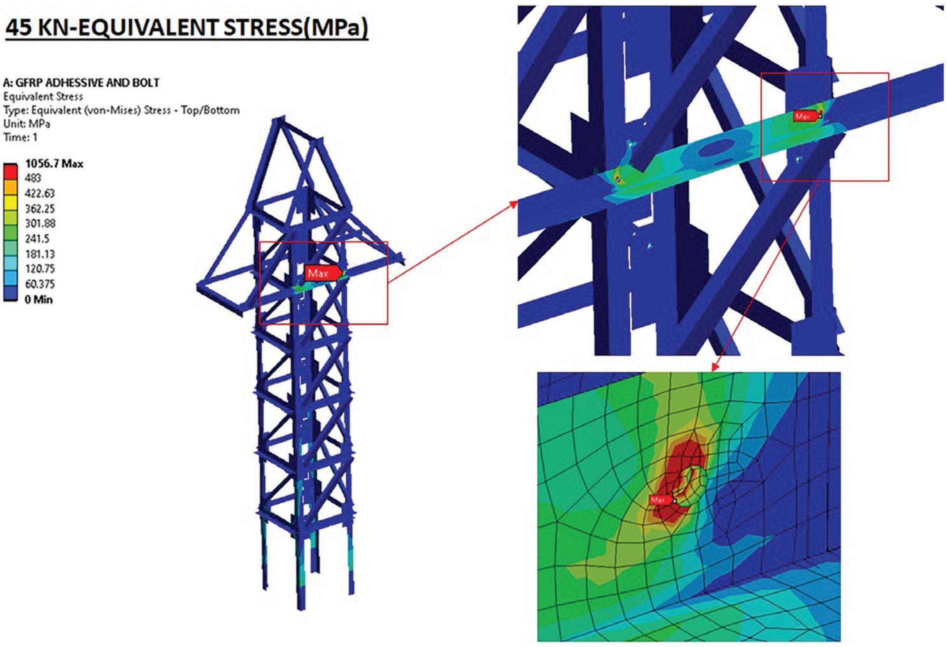

Figure 8: ANSYS model of 2 bolted hybrid GFRP tower.

Table 2: Load deflection details of hybrid GFRP tower using Ansys software.

LOAD IN kN	DEFLECTION IN mm
0	0
5	3.7
10	7.5
15	13.1
20	17.8
25	22.5
30	27.2
35	31.9
40	36.6
45	41.3

4. RESULTS AND DISCUSSION

4.1. Connections of GFRP angle sections

On observing the test results of the experiments conducted, it is found that the crushing force of different specimens of joints with various connections of GFRP angle sections ranges from 37 MPa to 615 MPa. Standard crushing force in MPa and the corresponding displacement in mm have been noted and compared. Four types of connections (2 bolted, 3 bolted, 4 bolted and adhesive) with 4 types of joints (butt joint, lap joint, hybrid butt joint, hybrid lap joint) have been prepared for this study. In each combination, 3 specimens were prepared and tested for load-displacement behaviour. The average value obtained is furnished in Table 3 and considered for discussions apart from the load-displacement curve for different specimens with combinations of different joints and connections. The test data like displacement (mm) and standard crushing force (MPa) observed in the experimentations upon various specimens and comparative crushing performance between GFRP connection combination specimen and GFRP angle specimen mean compressive stress of 451 Mpa from Table 1 are furnished in Table 3.

4.1.1. Crushing performance of GFRP angle 2 bolted connections with various joints

The load displacement curve for GFRP angle 2 bolted connections with various joints is shown in Figure 9. The crushing performance of GFRP pultruded angle 2 bolted connections with various joints such as butt and lap are

Table 3: Displacement and standard crushing force of various GFRP pultruded angle specimens & comparative crushing performance.

S.NO.	CONNECTIONS	DETAILS OF JOINTS/ CONNECTIONS COMBINATIONS	DISPLACEMENT (mm)	STANDARD CRUSHING FORCE (MPa)	COMPARATIVE CRUSHING PERFORMANCE BETWEEN GFRP CONNECTION COMBINATION SPECIMEN AND GFRP ANGLE SPECIMEN (MPa)
1	2 Bolted connections	Butt joint	73	381	↓70
2		Hybrid butt joint	82	583	↑132
3		Lap joint	90	297	↓154
4		Hybrid lap joint	44	556	↑105
5	3 Bolted connections	Butt joint	146	556	↑105
6		Hybrid butt joint	64	615	↑164
7		Lap joint	89	459	↑8
8		Hybrid lap joint	51	516	↑65
9	4 Bolted connections	Butt joint	68	240	↓211
10		Hybrid butt joint	53	411	↓40
11		Lap joint	85	426	↓25
12		Hybrid lap joint	70	79	↓372
13	Adhesive connections	Butt joint	60	604	↑153
14		Lap joint	8	37	↓414

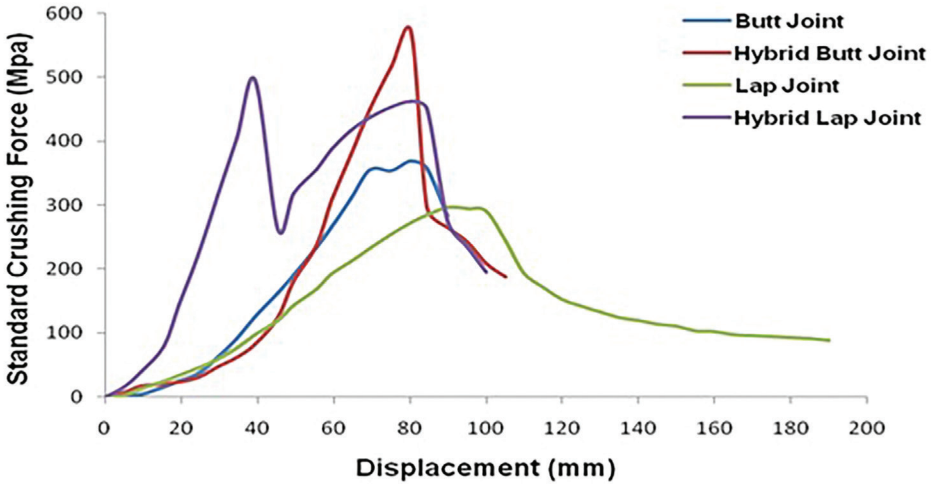

Figure 9: Load displacement curve for GFRP angle 2 bolted connections with various joints.

shown in different colours to have a better comparison among them. The load-displacement curve shows the best performance by angle 2 bolt hybrid joint with a crushing force of 583 MPa and a displacement of 82 mm.

4.1.2. Crushing performance of GFRP angle 3 bolted connections with various joints

The load displacement curve for GFRP angle 3 bolted connections with various joints is shown in Figure 10. The crushing performance of GFRP pultruded angle 3 bolted connections with various joints such as butt and lap are shown in different colours to have a better comparison among them. The load-displacement curve shows the best performance by angle hybrid 3 butt joint with a crushing force of 615 MPa with a displacement of 64 mm.

4.1.3. Crushing performance of GFRP angle 4 bolted connections with various joints

The load displacement curve for GFRP angle 4 bolted connections with various joints is shown in Figure 11. The crushing performance of GFRP pultruded angle 4 bolted connections with various joints such as butt and

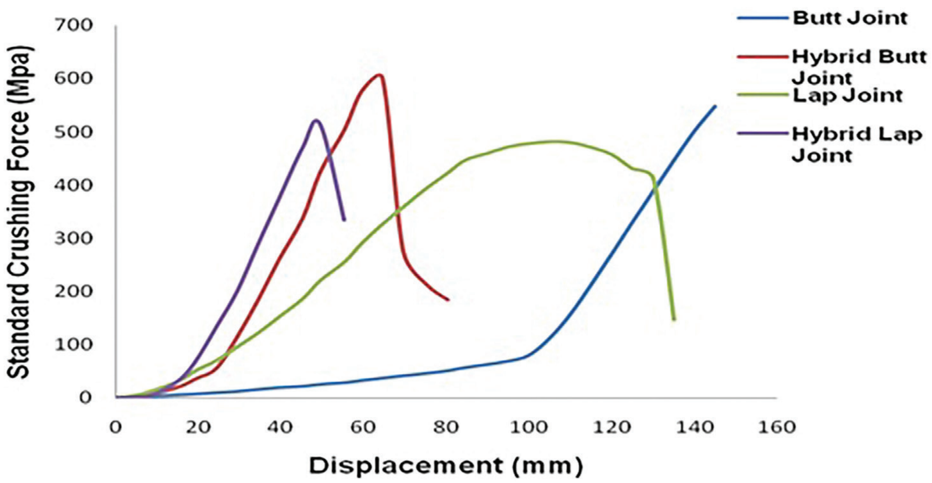

Figure 10: Load displacement curve for GFRP angle 3 bolted connections with various joints.

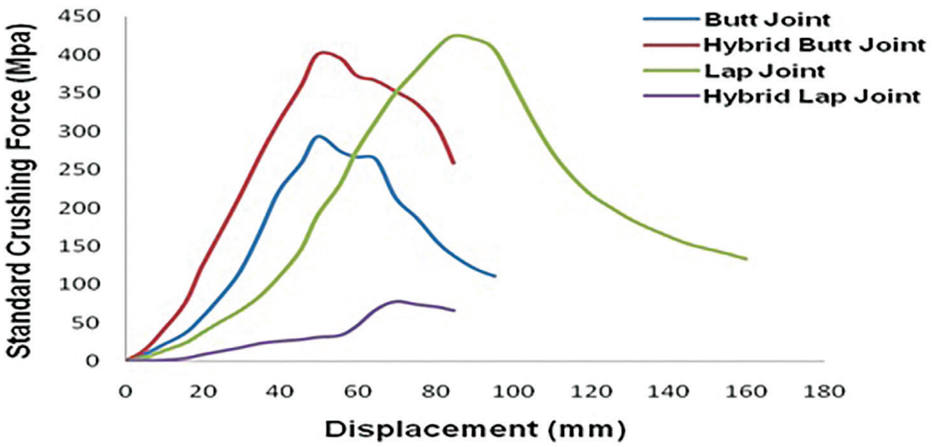

Figure 11: Load displacement curve for GFRP angle 4 bolted connections with various joints.

lap are shown in different colours to have a better comparison among them. The load-displacement curve shows the best performance by angle 4 bolted lap joint with a crushing force of 426 MPa and a displacement of 85 mm.

4.1.4. Crushing performance of GFRP angle adhesive connections with various joints

The load displacement curve for GFRP angle adhesive connections with lap and butt joint is shown in Figure 12. The crushing performance of GFRP pultruded angle adhesive connections with various joints such as butt and lap are shown in different colours to have a better comparison among them. The load-displacement curve shows that the best performance by angle adhesive butt joint with a crushing force is 604 MPa and a displacement of 60 mm.

By comparing the test results of standard crushing force and displacement as furnished in Table 3 and considering the plots of standard crushing force against displacement curve, some useful points have been derived and furnished in Table 4.

It is noted that among the 2 bolted connections group, maximum crushing force is noted for the hybrid butt joint, which is 1.5 times higher than the 2 bolted butt joint, 1.9 times higher than the 2 bolted lap joint and 1.05 times higher than the hybrid 2 lap joints. In the 3 bolted connections group, the hybrid butt joint exhibits a higher crushing strength which is 1.1 times higher than the 3 bolted butt joints, 1.3 times higher than 3 bolted lap joints and 1.2 times higher than the 3 bolted hybrid lap joints. In the 4 bolted connections group, the lap joint exhibits higher crushing strength, which is 1.8 times higher than 4 bolted butt joints, 1.04 times higher than hybrid 4 butt joints and 5.4 times higher than 4 bolted hybrid lap joints. In the adhesive connections group, the butt joint exhibits higher crushing strength which is 16 times higher than the adhesive lap joint. Among various

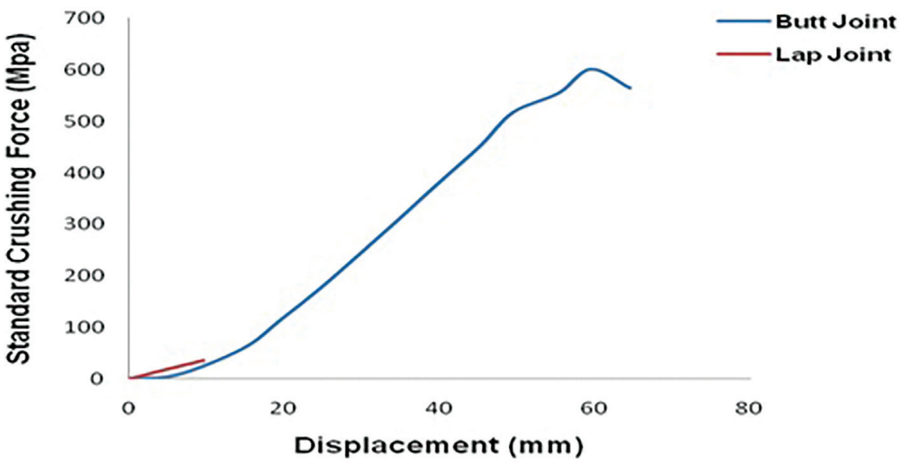

Figure 12: Load displacement curve for GFRP angle adhesive connections.

Table 4: Comparison of test results of different GFRP pultruded angle connections.

S.NO	DETAILS OF JOINTS/ CONNECTIONS COMBINATIONS	MAXIMUM CRUSHING FORCE	COMPARISON
1	2 Bolted connection	The hybrid butt joint exhibits the highest crushing strength.	• 1.5 times higher than 2 bolted butt joints • 1.9 times higher than 2 bolted lap joints and • 1.05 times higher than hybrid 2 lap joints
2	3 Bolted connection	The hybrid butt joint exhibits the highest crushing strength.	• 1.1 times higher than 3 bolted butt joints, • 1.3 times higher than 3 bolted lap joints and • 1.2 times higher than hybrid 3 lap joints
3	4 Bolted connection	The lap joint exhibits the highest crushing strength.	• 1.8 times higher than 4 bolted butt joints, • 1.04 times higher than 4 hybrid 8 butt joints and • 5.4 times higher than 4 hybrid lap joints
4	Adhesive connection	The butt joint exhibits the highest crushing strength.	• 16 times higher than adhesive lap joints

joints, the butt joint exhibits more crushing force than the lap joint. Hybrid butt joint connection withstands more standard crushing force than other joints. This is because of the adhesive and additional GFRP plates provided over the surface of butt joints. Among the lap joints, the maximum standard crushing force of 556 MPa is taken by a 2 bolted hybrid connection with a displacement of 44 mm. The standard crushing force for a 2 bolt hybrid connection is 15 times higher than adhesive joints.

As the adhesive connection in the lap joint is very weak, it exhibited lower performance. From the displacement point of view, hybrid butt and lap joint exhibit better performance with standard crushing force when compared to other joints. On examining the crushing performance of different connections with various joints, 2 bolt hybrid butt joints, 3 bolt hybrid butt joints, 4 bolt hybrid butt joints and adhesive butt joints are the best crushing loads and lesser displacement.

4.2. GFRP angle tower with hybrid connection model

The design load is chosen to approximate the wind load on top of the tower model at a typical height of 3 m, based on the norms followed by the previous researchers [16, 36, 37]. The tower model is subjected to lateral load testing. The positioning of load cell and jack for applying load is shown in the Figure 7. The load is applied in 5 kN increments until the design loads were reached. The tower model withstood almost the design load successfully. Table 5 depicts the load-deflection behaviour of the GFRP tower model under lateral loads. From the load versus deflection behaviour, the tower model has experienced a maximum force that is greater than 45 kN. The deflection of the tower model exhibited 38 mm for 45 kN loads. Figure 13 depicts the deflection behaviour of TLT model by experimental and numerical analysis.

Table 5: Deflection of GFRP tower model under lateral loads.

LOAD IN kN	DEFLECTION IN mm			
	TRIAL 1	TRIAL 2	TRIAL 3	AVERAGE
0	0	0	0	0
5	8	5	2	5
10	10	6	13	10
15	11	10	18	13
20	12	12	26	17
25	16	16	32	21
30	20	22	36	26
35	26	24	42	31
40	30	30	45	35
45	33	34	48	38

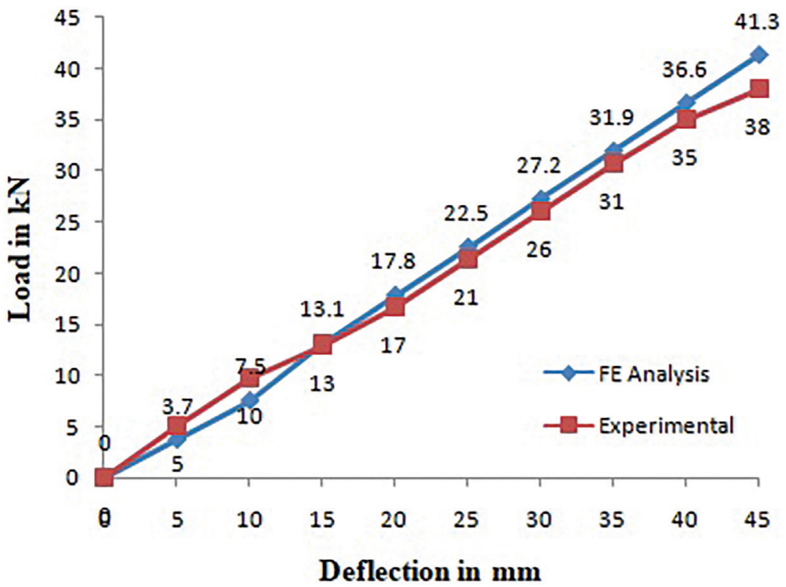

Figure 13: Deflection behaviour of TLT model by experimental and numerical analysis.

From the deflection behavior of the GFRP tower with the hybrid connection model, the maximum deflection of the tower from numerical analysis exhibits close agreement with experimental results. Also, the tower withstood design loads through experimental and numerical analysis.

5. CONCLUSION

For TLT construction, GFRP has certain advantages over traditional steel materials. The extensive use of GFRP composites in Civil Engineering infrastructures such as transmission line towers has been limited due to a lack of understanding of the behavior/design requirements of structural systems, structural components, and structural connectors. Some of these criteria are being considered in the current investigation.Based on the experimental work, The outcome of the present research work leads to the following conclusions:

1. In this study the effect of crushing force performance of GFRP angle sections of different joints with various connections under a speed rate of 1 mm/min is investigated. Based on the discussion of the results obtained, it can be concluded that:
   a. The correlation between the number of bolts increases and the decrease in energy absorption is observed.
   b. A hybrid butt joint connection is most suitable and withstands high crushing force or energy absorption. The best connections are identified.

2. The failure mode and load vary as the plate width and edge distance increase, confirming the results published in the literature for plate-to-plate connections. In relation to net-compression strength, the influence of plate width and edge distance on connection efficiency was explored, and it is revealed that an edge distance to hole diameter ratio of five provides the maximum efficiency.
3. The efficiency is unaffected by edge distance-to-hole diameter ratios greater than five; hence, the maximum edge distance-to-hole diameter ratio is five. In the bearing failure mode, a wide plate with an acceptable edge distance and a width-to-hole diameter ratio greater than 5 fails.
4. Due to the bigger net-sectional area and distinct material structure of the angle member in contrast to the plate, the angle section that failed in the net-compression mode showed a higher cross-correlation coefficient than the corresponding plate failure mode. Performance evaluations of GFRP composite TLT and the stability performance of the hybrid connection have been evaluated by both experimental and numerical using Ansys software.
5. The test results show that GFRP TLT with hybrid connection exhibits very less deflection of 17.05 mm. The maximum tensile stress is found to be 411.5 MPa from the stress model.
6. The deflection of the GFRP tower is 73% lesser than the steel tower and the maximum stress developed in the GFRP tower is 30% lesser than the steel tower. Hence it can be concluded that GFRP composite TLT with a hybrid connection is able to withstand wind loads. The GFRP tower is economical for long term while considering the recurring maintenance cost of a conventional steel TLT.

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