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Research Article

Design and Application of a Gripping Apparatus for Torsion Testing of Aluminum/Composite Tubes

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ABSTRACT

As is known, hybrid composite shafts with fibers and metals offer remarkable improvements in terms of mechanical performance, and research is still ongoing in this field. Due to the nature of torsional loading, it is seen that various holding apparatuses are applied for specimens of different diameters to test the specimen without slipping between the test jaws, especially for large parts. This study examines specimen types and connection elements used in torque tests, and a practical solution that can be used in universal testing machines is investigated. In this context, experiments were carried out for unreinforced aluminum tubes and [±45$_2$/Al] arrayed specimens using screw clamp connection and shape-bonded designs. It was found that reinforcement of the clamping region of the specimens with an additional layer in hybrid tubes is a preferable solution for shape-bonded connections.

1. Introduction

As it is known, the search for lightweight and high-strength composite materials has increased the use of composite materials in many engineering applications, especially in aerospace [1-7]. In particular, using composite materials in the automotive industry to reduce carbon emissions by reducing vehicle weight offers remarkable results [8]. The fact that the shafts used in power transmission are generally made of steel and manufactured in two parts is an important constraint in obtaining the desired frequency (natural in bending) values due to the high material density. Composite materials are a good alternative for shaft manufacturing, as their light weight allows for monolithic production [9,10]. Different performance demands in the application have led to using different fibers alone or as hybrids in the same matrix in composite shaft manufacturing [11-13]. However, the fact that composite materials are generally not as ductile as metals limits the toughness values of tubular structures and may cause them to behave sensitive to instantaneous loading. For this reason, the use of metal (aluminum)/composite shafts has been brought to the fore, and the effects of fiber and epoxy type, fiber winding angle, and stacking sequence on shaft performance have been investigated[14-16]. In evaluating the performance of composite shafts, static torsion tests are mainly used, and due to the nature of the test method, tightening problems are often encountered in the fasteners.

In the studies conducted in the literature for different diameters and lengths, pipe (tube)[17-19] and dog-bone [20-23] or specimen types with additional layers added to the clamping zones [24, 25] were used as test specimens (Figure 1). To prevent radial deformation in the jaw clamping area, plug-shaped parts of different material types were used in the specimens. In dog bone specimens, removing the middle part with a lathe, etc., applications may cause various problems (surface roughness, fiber breakage, heating, etc.) as a result of the process. To avoid

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damaging the fibers, machining must be done with high precision.

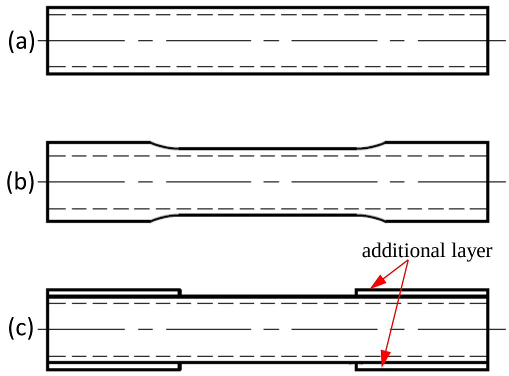

Figure 1. Schematic representation of the test specimens: (a) pipe (tube), (b) dog bone, and (c) with an additional layer applied

In experiments where the specimen diameters were below the maximum holding diameters of the test equipment, pipe or dog bone specimens were found to be successful. Tariq et al. [12] used straight pipe specimens, and the experiments were completed with the maximum torque values of 200 Nm and the clamping force of the testing machine. Similarly, Suresh et al. [20] obtained successful test results on dog bone specimens using only the test machine clamping force. In another study [22] using specimens prepared by adding an additional layer to the clamping zone, the specimens were directly connected to the testing machine, and experiments were carried out. The torque values obtained in this study are below 100 Nm. However, the maximum torque and/or maximum diameter values of multi-layered or large-diameter specimens were beyond the capacity of the testing machines, which led to the investigation of different clamping designs.

In the literature, many studies use glued [20, 23, 24] and shape-bonded designs [22, 25] for specimens above the jaw connection diameter capacity of the testing machine. Apart from this, attempts have also been made to develop connection equipment in which both methods are applied. In such applications, selecting the adhesive according to the clearance amount, surface condition, and moment to be transmitted in the connection would be appropriate.

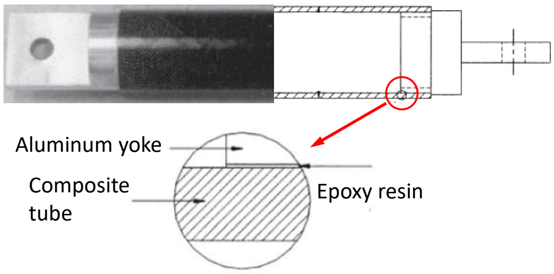

Figure 2. An example of an adhesive bonding connection[26]

Jin Kim et al.[26] conducted experiments for different yoke thicknesses and bond lengths in their study, in which they achieved torque transmission of up to 5000 Nm using epoxy adhesive (Figure 2). As a result of the experiments, they determined that for a 90 mm diameter shaft, with an adhesive thickness of 0.2 mm and a yoke thickness of 4.8 mm, a bond length longer than 16 mm is required for torque transmission of 3500 nm. Similar studies emphasized that the bond area (length or diameter) is important for bonding joints. In another study, Won Tae Kim et al. [27] bonded composite tubes and steel flanges and investigated the torque transmission capabilities of various bonding types. They investigated single-sided and double-sided bonding for hexagonal, circular, and elliptical cross-sections and reported that double-sided bonding gave more effective results, as expected (Figure 3).

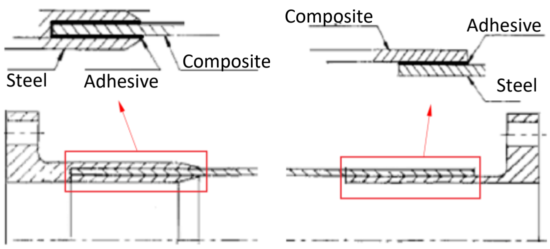

Figure 3. An example of single- and double-sided adhesive bonding[27]

In studies where torque transmission is realized with shape bonding, there are applications where thread geometries are machined into tubes and metal fasteners, as well as studies where flanges and bolts are used together. Kim et al. [28] reinforced the aluminum tube from the internal reinforcement and provided torque transmission by tight fitting method by machining a large number of small threads on aluminum yokes and tubes. They developed an optimum design for the threads according to the number and shape of the threads in the fasteners (Figure 4). In another similar study [17], tests were successfully completed using bonding and threaded interference fit method together, and torque transmission of 4000Nm was achieved.

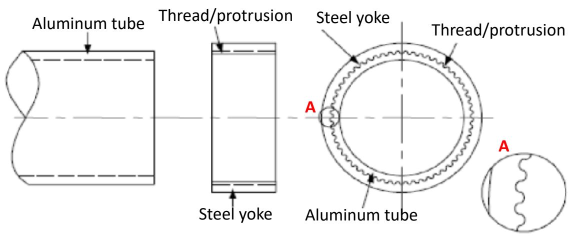

Figure 4. Torque transmission by machining threads/protrusions into specimens[28]

In another study, Sevkat et al.[29] performed tests using both bonding and shape bonding by using epoxy at the ends of the composite tube and bonding it to steel square profiles (Figure 5). Although it was seen that the obtained connection type could carry a static torque up to 1500 Nm, it was understood that the connection was inadequate under dynamic conditions.

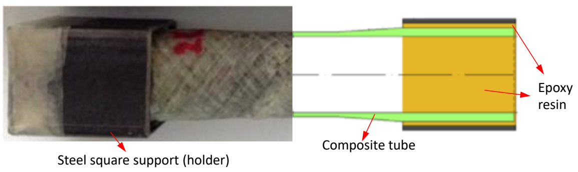

Figure 5. Steel square support (holder) and specimen geometry [29]

In another study using a screw-clamp connection, Soykok et al. [30] completed torque tests using a socket wrench-spindle assembly with a pair of holding dies, each consisting of two compression jaws (Figure 6). While the socket wrench provided torque transmission, it also prevented the holding dies from crushing the pipe. The maximum torque value reached in the study was around 25 Nm.

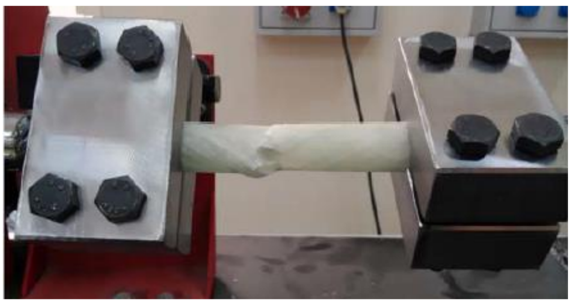

Figure 6. An example of a screw clamp connection [30]

In the study [31], where torque transmission was achieved by drilling holes in the composite tubes from their end sides, the tubes were connected to the torque device with the help of a flange (Figure 7). The beginning of damage in the hole area in the research specimens is seen.

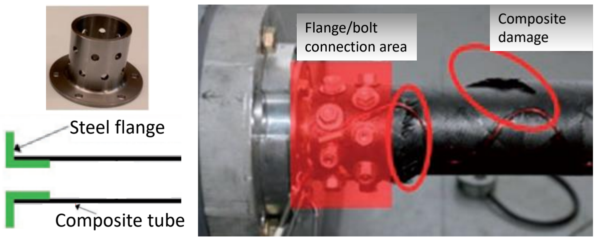

Figure 7. Use of hollow flanges and bolts for torque transmission [31]

In another study [25], in which bolts were used for torque transmission, experiments were carried out on a torque test rig specially manufactured for the specimens (Figure 8). In this system, the linear motion generated by the actuator is converted into a force pair by means of wires wound on the cylinder, which produces pure torsional stress in the specimen located on the same axis. The composite tubes used in the experiments were reinforced with additional layers at the ends to reinforce the existing wall, thus preventing damage to the perforated part. It is reported that this method successfully completed the tests with torque values up to 3250 Nm.

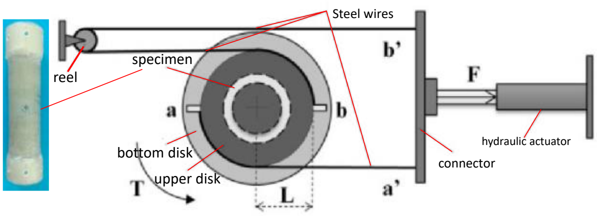

Figure 8. Device for converting tensile force into pure torsion [25]

When the literature is examined, it is understood that the torque amounts and test specimen diameters that can be transmitted with the jaw clamping force of universal testers are limited, and the assemblies used for high torque transmission require special designs. This study experimentally investigated static torque capability for sizes above the specimen gripping diameter capacity of the jaws using a universal testing machine with screw-clamp and shape bonded (lathe chuck and bolts) connection methods.

2. Experimental Study

Within the scope of the study, torque transmission capability was investigated in the universal testing machine using two different methods. Hybrid tubes with 45º fiber orientation, which is of primary importance in torque transmission, were produced for the tests. Tests are planned to be carried out for aluminum tubes and [$\pm45_2$/Al] sequenced specimens.

2.1. Sample fabrication

Al6063-T5 aluminum alloy tube, glass fiber, and epoxy resin were used to prepare the test specimens. Due to its advantages, the filament winding method was used to fabricate composite tubes[32]. The winding equipment is shown in Figure 9, and the winding accuracy for this equipment was found to be ±0.46 degrees. The post-winding curing process of the samples was carried out at room temperature for 24 hours and then at 40 ºC for 2 hours. The fiber volume ratio of the post-production samples was determined as 60±1%. The thickness of the composite layer wound on the tube with ±45º orientation was determined to be 0.69 mm.

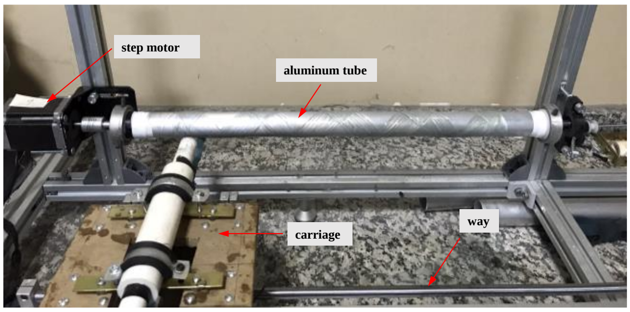

Figure 9. Filament winding equipment used in the fabrication of specimens

The cured specimens were reinforced with carbon fibers at the ends, as shown in Figure 10. The jaw clamping areas were sanded to increase the adhesion effect, and carbon reinforcements were made using the hand lay-up method.

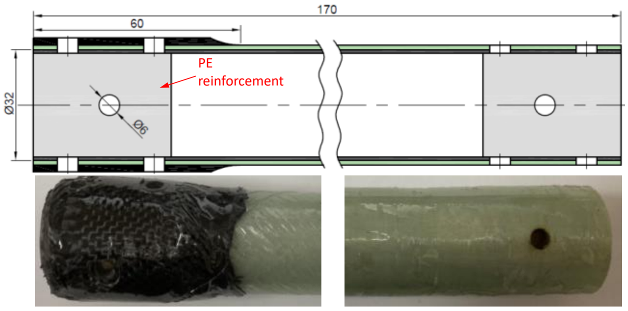

Figure 10. Torque test specimens

2.2. Experimental setup

Within the scope of the study, all torsion tests were carried out at 0.2 º/s speed, 1100 Nm torque capacity MTS 809 Axial/Torque testing machine with angle control at SAU, SARGEM. Since the specimen diameters (in Figure 10) used in the torsion tests were above the jaw grip diameter limit of the testing machine, two different connection types were considered. In the screw clamp connection method, the specimen is placed between two jaws, the experiments are carried out, and the jaw and specimen interfaces are roughened by sandblasting to contribute to the friction force. The tightening force of the bolts determines the pressure's intensity on the contact surfaces. It is obvious that the fact that the steel ring acting on the surface of the aluminum tube is screwed to the tube separately will prevent sliding on the surfaces of the ring and the Al tube (Figure 11).

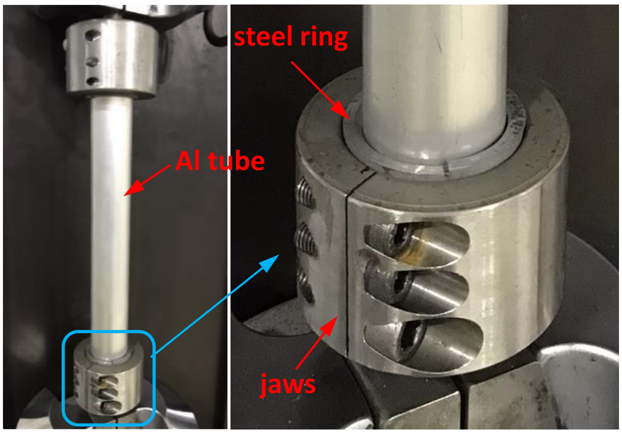

Figure 11. Screw clamp connection setup

As it is known since the pressure distribution along the contact area on the surface (here tube-ring-jaw) is not uniform, it is accepted that the developing force occurs due to an average pressure acting along the projection area (*b.d*) in the part and the normal (F_n) and friction (F_s) forces are calculated separately for the seating area of both halves (Equation 1-3). Accordingly, the friction torque due to friction will determine the torque capacity to be transmitted.

$$F_n = d * b * p \tag{1}$$

$$F_s = \mu * d * b * p \tag{2}$$

$$M_s = 2 * F_s * \frac{d}{2} \tag{3}$$

In the equations, d is shaft diameter, b is jaw width, D is jaw diameter, μ is friction coefficient, and p is pressure [33,34].

The specimen dimensions used in the shape-bonded method using chucks and bolts are given in Figure 10. The small diameter holes on both sides of the specimen are for the fixing pins that prevent the specimen from slipping during the test. This way, a constructive precaution was taken to prevent slippage. A polymeric (PE) material plug was inserted through the tube to support the clamping zone of all specimens so as not to affect the tube wall in the jaw clamping effect (Figure 12).

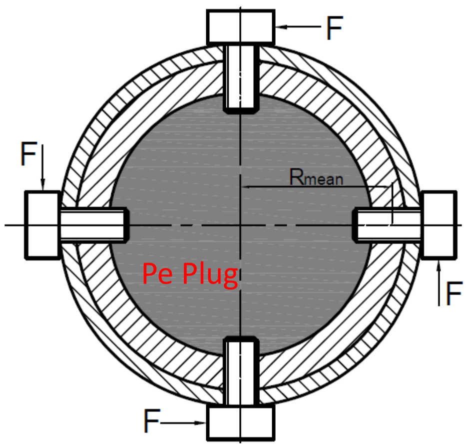

Figure 12. Schematic representation of bolt connection

As is known, bolted connections are normally designed to carry loads in the axial direction. However, loads perpendicular to the bolt axis create shear and bending stresses on the bolt shaft. If there is no clearance between the part and the bolt, it is sufficient to consider only the shear stress. The equations used for the safety stress control are given in Equations 4 and 5.

$$T = 4 * F * R_{mean} \tag{4}$$

$$\tau = \frac{F}{A} \le \tau_s \tag{5}$$

Here, R_{mean} is the mean radius, F is the force acting because of the torque transmitted to the bolts, τ is shear stress, τ_s is safety shear stress, and A is the bolt cross-sectional area. It is important for the tests to determine the bolt material and number according to the torque value to be transmitted[33,34]. The torsion test setup used in the experiments is shown in Figure 13.

3. Results and Discussion

The results of the experiment with the Al tube in the screw clamp connection are given in Figure 14. When the test results are examined, it is understood that torque transmission up to approximately 200 Nm values can be achieved. However, when the deformed tube is examined, it is concluded that a reliable experiment cannot be performed due to slippage in the clamping areas and the screws cutting the tube. While emphasizing that the connection will provide practicality for lower torque values, it has shown that it is not suitable for hybrid-composite parts where higher torque requirements may be required. In the tests of the aluminum tube, it was seen that the torque transmission could be performed successfully with the help of the bolt; although insignificant deformation occurred in the bolt connection area after the test, significant torsional deformations could be created in the tube body (Figure 15.a). Detailed strength calculations should be considered when determining the size and number of holes in cases where higher torque is required, depending on the material's tube size/bar thickness and strength values. In the [±45_2/Al] tests of the composite specimens shown in Figure 15.b, stress concentrations in the hole region of the specimen caused cracks in the epoxy. The brittle nature of the composite material also contributed to the damage formation. The fact that the experiment resulted in fracture in this way should be considered a failure for the test setup. However, this method can be controlled if the damage involves geometric discontinuities with higher stress concentrations outside the specimen connection points [31, 35]. In this context, in a study using a similar torque transmission method [31], the specimen was subjected to ballistic impact (7.62 mm bullet) before or under torque loading. Therefore, the connection method was found not to pose a problem in terms of static torque transmission. In addition, as expected, the damage in the dog bone specimens in the literature started from the discontinuity points (holes) that have a notch effect [29]. [$\pm45_2$/Al] specimens in which carbon fiber was reinforced in the clamping regions of the specimen, the damage occurred not in the connection holes but in the middle part of the specimen, that is, in the thinned part, in accordance with the literature (Figure 15.c). When the cross-sectional view of the hole region of this specimen is examined, it is clearly seen that there is no damage in the hole region (Figure 15.d). Therefore, it is understood that the additional layer (carbon fiber) reinforcement maintains its structural integrity around the hole under stress. From the torque-angle curves of the specimens given in Figure 16, it is seen that the maximum torque value is much higher in the carbon fiber reinforced specimen where the notch effect is reduced. In this specimen, the damage occurs in such a way that the cross-section completely loses its load-carrying capability (catastrophic), while in the unreinforced specimen, the damage that starts in the notch region progresses relatively gradually. The difference in the slope of the curve in the elastic region can be said to be due to the difference in section stiffness along the specimen. Here, although the adaptation of the equipment (lathe chuck) to the jaw of the universal testing machine ensured that the torque was transmitted at the desired level during the experiment without causing slippage, some deviation in the measured rotation angle can be expected. This is due to the fact that the additional equipment used extends the torsional length and ultimately only has a certain structural rigidity. For a standard 200 mm diameter four-legged chuck, it was found that the test device detected three degrees more rotation.

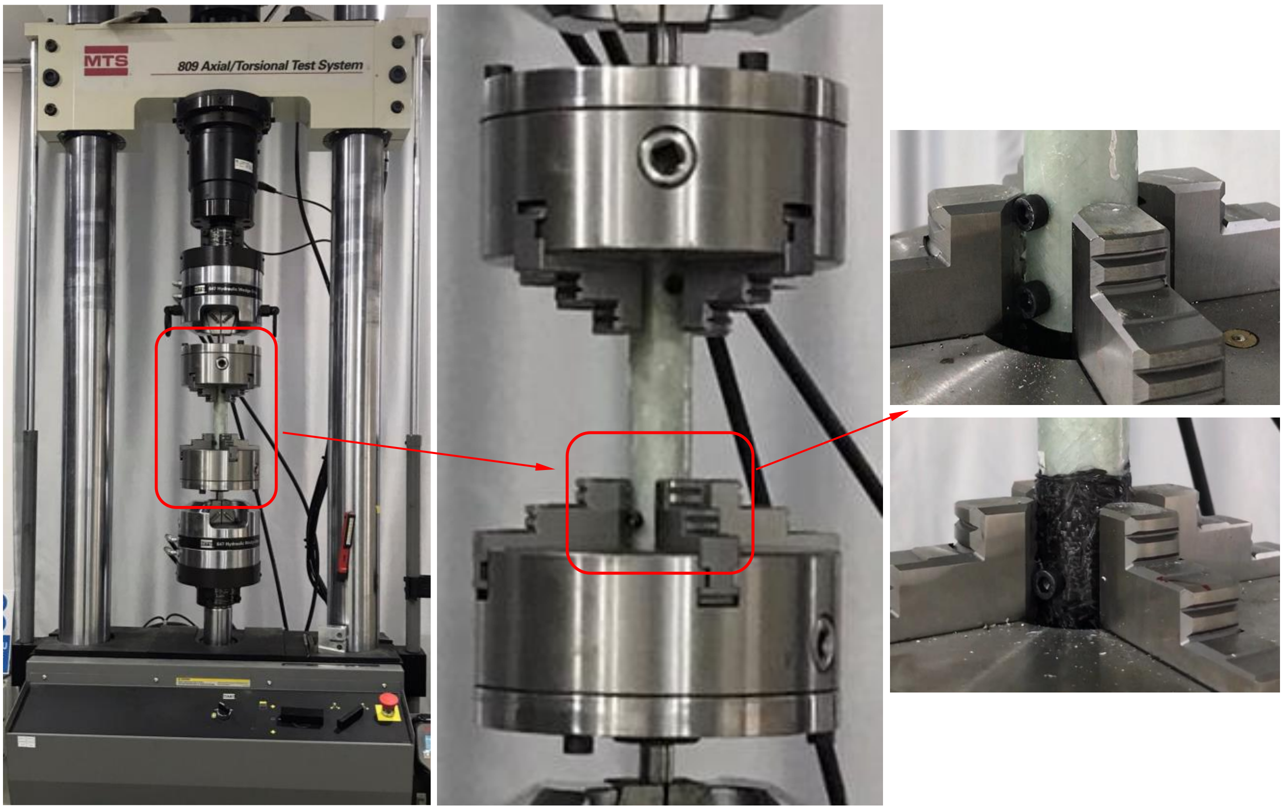

Figure 13. Assembly for using a four-jaw lathe chuck as a gripper in a universal testing machine

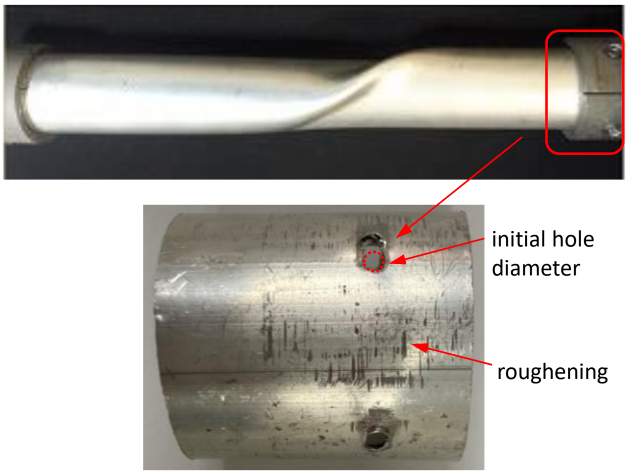

Figure 14. Roughening of the tube surface (as a result of sliding) and deformation of the screw holes in the screw clamp/friction assembly (This surface is under the steel ring)

4. Conclusion

In this study, the specimen types of cylindrical composite tubes and the connection equipment are mainly reviewed, and their shortcomings and advantages are discussed. Experimental studies have shown that the screw clamp connection can provide a solution for low torque values (200 Nm). In the shape-bonded method, it has been determined that the bolt connection reduces the mechanical performance due to local stress concentration in torque transmission, and reinforcing the bolt areas with an additional layer can provide a solution for the problem in question. In a universal testing machine with static torque capability, when clamping jaws cannot be used, the four jaws lathe chuck connection was found to be a practical and cost-effective solution because it allows both the specimen to be gripped by clamping and the chuck legs to form a shape bond for the bolts. This method can also be used in special equipment designed for high torque values (>2200 Nm) that challenge the capacity of the universal testing machine.

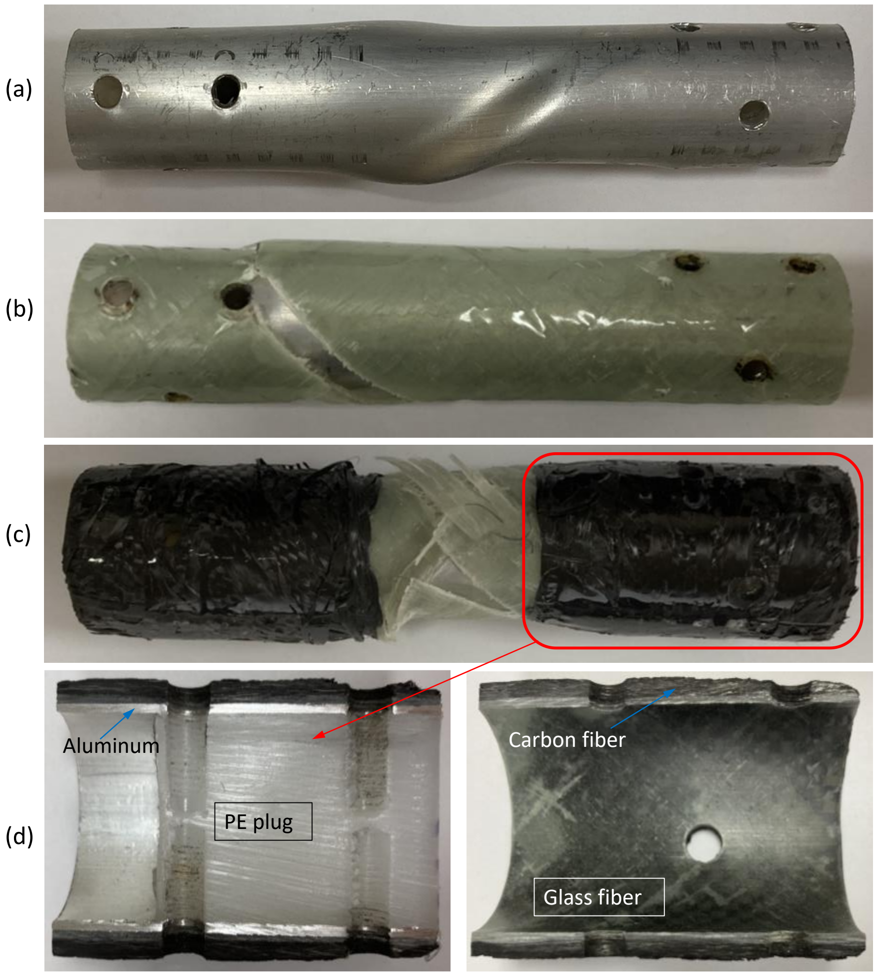

Figure 15. Damage images of the specimens: (a) aluminum tube, (b) [$\pm45_2$/Al] specimen, (c) [$\pm45_2$/Al] specimen with additional carbon reinforcement, and (d) post-test cross-section of the specimen with additional carbon reinforcement

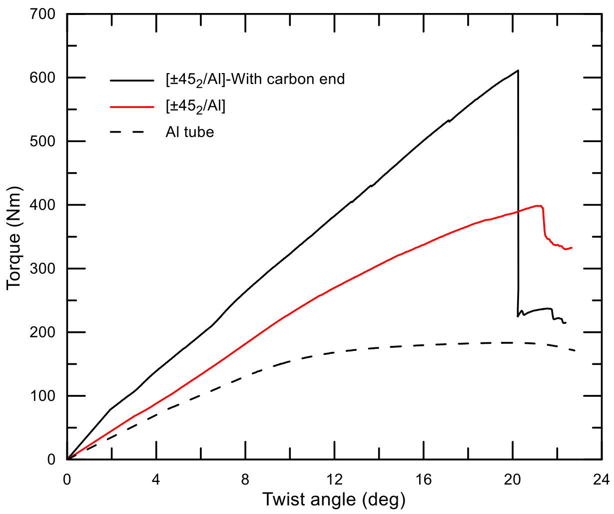

Figure 16. Torque-angle curves of the specimens

Article Information Form

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Authors' Contribution

The authors contributed equally to the study.

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No conflict of interest or common interest has been declared by the authors.

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