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EXPERIMENTAL INVESTIGATION OF THICK-WALLED COMPOSITE TUBES UNDER AXISYMMETRIC LOADING

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ABSTRACT

This paper addresses thick-walled composite tubes under axisymmetric loading (axial and torsional). A thick-walled tube is manufactured from glass/epoxy composite material, having thickness to outer diameter ratio greater than 0.1. For this highly thick-walled tube, a developed test rig is built to apply a pure torsional load and measure the torsional stiffness of the tube. Adding to that, the tube is tested under a compressive axial load. This is done to validate the existence of the axial-torsional coupling and to experimentally complete the understanding of the tube structural behavior under axisymmetric loading conditions. The testing results are also used to validate the available theoretical methods used in analysis and design of composite tubes under torsion.

KEYWORDS

Filament winding, TGA, torsional stiffness, extensional stiffness, axial-torsional coupling.

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NOMENCLATURE

EA	Axial stiffness (N)
GJ	Torsional stiffness (Nm^2)
P	Axial force applied. (N)
T	Torque applied (N.m)
$G_{eff,n}$	The effective shear modulus of the layer n with [θ/-θ] configuration. (GPa)
J_n	The layer polar moment of inertia. (m^4)
$G_{xy,n}$	Shear modulus of layer n (GPa)
(X_1),(X_2)	Coefficients in terms of the composite material properties [4]
r	Outer radius of the tube (m)
v^f	Fiber volume fraction
w^f	Fiber weight fraction
w^m	Matrix weight fraction
ρ^m	Matrix density (kq/m^3)
ρ^f	Fibers density (kq/m^3)
γ_{xy}	In plan shear strain (radian)
$(\eta_{x,xy})$, $(\eta_{y,xy})$	Coefficients of mutual influence of the first kind
ε	Axial strain and of the deformed tube, respectively (μ ε)
α	Winding angle

INTRODUCTION

The use of composite materials is ever increasing in commercial and defense industry applications. One of the most commonly used structures is thick walled -laminated composite tubes that can be used for many applications such as aerospace industry, mechanical power transmission, and pressure vessels. Full utilization of the characteristics offered by the laminated composite tubes requires an understanding of the structural behavior under different loading conditions.

A previous work was done by El-Geuchy and Hoa [1] to understand the structural behavior of thick-walled composite tubes subjected to pure bending load. They performed a parametric study and an experimental program to identify the effective parameters that govern tube behavior under bending including its failure behavior and bending stiffness. It is also required to understand the structural behavior of thick-walled composite tubes subjected to axisymmetric loadings, theoretically and experimentally. Theoretically, Jolicoeur and Cardou [2] had used Lekhnitskii theory [3] to obtain a general analytical solution for thin and thick-walled composite tubes under axisymmetric loadings, as shown in the following equation:

$$\begin{bmatrix} P \\ T \end{bmatrix} = \begin{bmatrix} EA & B_{12} \\ B_{21} & GJ \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \gamma_{xy/r} \end{bmatrix} \tag{1}$$

Their solution is based on the three-dimensional elasticity theory, making it to be considered as the most convenient method for the analysis of thick-walled composite tubes. The obtained solution shows the coupling behavior between axial and torsional deformation which is represented as the axial-torsional coupling parameter (B_{12}). It is recommended to check, experimentally, the existence of this coupling parameter when the tube has a balanced laminate configuration. A. M. Musrati et. al.

[4] have done a theoretical study and derived a simple and accurate closed form equation to design and calculate the torsional stiffness of both thin and thick-walled composite tubes of $[(\theta/-\theta)_1/(\theta/-\theta)_2/---/(\theta/-\theta)_N]$ configuration. Theoretically, it was predicted that the torsional stiffness GJ mainly dependent of the interaction effects at the interface of the laminas of [θ/-θ] configuration. The closed form equation is formulated as:

$$GJ = \sum_{n=1}^{N} G_{eff,n} * J_n = \sum_{n=1}^{N} \frac{G_{xy,n} * J_n}{(\eta_{x,xy} X_1 + \eta_{y,xy} X_2 + 1)_n} \tag{2}$$

Experimentally, many papers conducted the testing of thin-walled composite tubes under torsion. Yang and Zhang [5] carried out their experiments on a thin-walled tubes made of carbon/epoxy to assess the predictions of their derived formula for torsional stiffness of thin-walled tubes. Their derivation was based on the classical lamination theory which was suitable for tubes having thickness to outer diameter ration less than 0.05. Parnas and Akkas [6] investigated the response of thin walled filament-wound composite tubes under pure torsional loading. They compared their experimental results with those obtained from the finite element method.

A few experimental works were conducted on thick-walled composite tubes subjected to axisymmetric loading especially axial loading and torsional loading.

In this paper, experimental testing is presented for a thick-walled composite tube. A glass/epoxy composite tube is manufactured using the filament winding method. A special test rig is designed and constructed to perform a pure torsional load for this thick-walled structural member. This is done to understand the behavior of this type of structure under torsion, and to validate the predictions presented in Refs. [2] and [4]. The tube is also tested under axial compression loading to validate the existence of the axial-torsion coupling parameter (B_{12}), presented in Ref. [2], when the tube has [θ/-θ] laminate configuration. In the following sections, the performed steps of the experimental work are presented.

MANUFACTURING OF THE LAMINATED COMPOSITE TUBE

The tube is made using the filament winding process as shown in Fig.1. The fabrication steps were done in the Fiber Glass Factory, located at ABOROASH, 6th October City. The tube was made of epoxy matrix material with E glass fibers. The fibers were supplied from the Chinese JUSHI Company of commercial name E6-CR glass fibers, while the resin was supplied from Saudi Arabia, known as SIROPOL-8340. This type of resin system was cured at room temperature without further need to be placed in a curing oven. The properties of the used materials are presented in Table 1.

Dimensions of the desired tube are: 3000mm length, 9mm thickness, and 64mm outer diameter. The winding configuration of $[45/-45]_{12}$ is selected because it yields the maximum value of the tube torsional stiffness (GJ) [7].

To achieve the desired configuration of the fabricated tube, the filament winding machine is adjusted where the carriage speed and mandrel rotation are regulated to

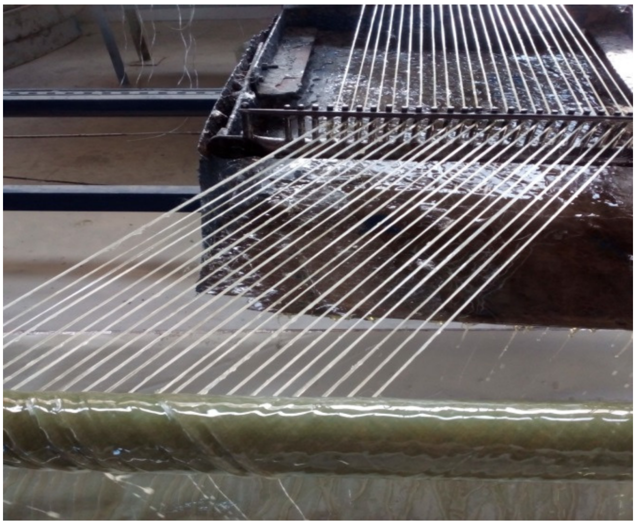


Fig. 1. Manufacturing of the composite tube by filament winding machine.

Table1. Properties of the used materials.

	E6-CR glass fibers	SIROPOL 8340 (Epoxy)
Young modules (GPa)	82	9.3
Poisson ratio	0.3	0.22
Density (kg/m^3)	1150	2650

generate the desired winding angle, as shown in the following equation [8]:

$$\tan \alpha = (\pi * \text{Diameter of mandrel} * \text{rotation speed}) / \text{carriage speed} \quad (3)$$

The manufacturing parameters are listed in Table (2).

Table 2. Manufacturing parameters of the filament wound composite tube.

Manufacturing Parameter	Value
Band width, [mm]	25.54
Mandrel rotating speed, [rpm]	30
Carriage axial speed, [m/min]	4.3
Number of circuits/layer	1
Number of patterns/layer	1
Number of layers	12

Determination of the elastic properties of the composite material is presented in next sub-section.

The Material Elastic Properties

This part presents the determination of the elastic properties of the used composite material. These elastic properties depend on those of the fibers and the matrix materials listed in Table (1). The stiffness properties of the composite material are strongly dependent on the fiber volume fraction, which can be determined from the weight fractions of the Fibers and the matrix in the composite tube using the following formula as presented in Ref. [7]:

$$\mathrm{v}^{\mathrm{f}} = \frac{\rho^m w^f}{\rho^m w^f + \rho^f w^m} \tag{4}$$

Weights of the fibers and matrix (w^f and w^m) were found out by performing the thermo-gravimetric analysis (TGA) test. It was carried out for a sample taken from the fabricated tube using an instrument of type “TGA Q500”, supplied form TA Instruments as shown in Fig.2. This instrument is available at the Science and Technology Center of Excellence (STCE).

Fig. 2. The used TGA Q500 instrument.

The TGA test result is shown in Fig.3. It is observed that the degradation temperature of the resin is at 379.45 ^{o}C. The fibers and matrix weight fractions were also determined as follows: w^f=0.572 and w^m = (1-w^f). By substituting of the weight fractions and the densities of the constituents in Eqn. (3), the fiber volume fraction of the tube is determined as (36%). It is assumed that the void content in the composite material is negligible.

The longitudinal Young's modulus $\mathbf{E_1}$, major Poisson’s ratio $\boldsymbol{\nu_{12}}$, the transverse Young’s modulus $\mathbf{E_2}$, and the in-plane shear modulus $\mathbf{G_{12}}$ were determined directly by substituting the obtained fibre volume fraction and the mechanical properties of

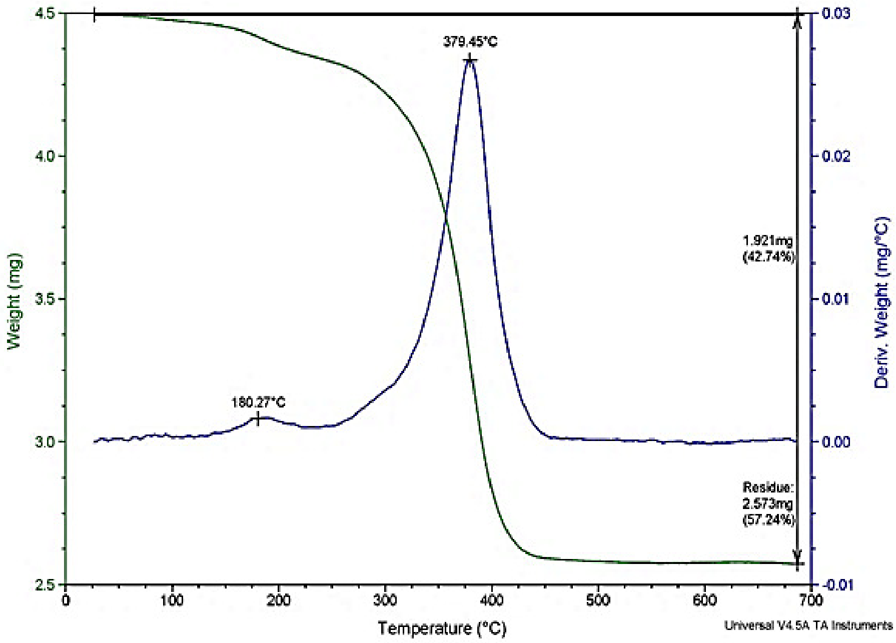


Fig. 3. TGA test result for a sample taken from the composite tube.

the raw materials into the rule of mixture relation, Ref. [8], as shown in the following equations.

The obtained mechanical properties of the tube are listed in Table 3.

Table 3. Average elastic properties of the used composite tube.

v^f	E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)
0.365	35.849	16.146	0.2707	6.357

TEST RIG SETUP

To obtain the torsional stiffness of the composite tube experimentally, a test rig is constructed for applying a pure torsional load, as shown in Fig. 4.

The pure torsion was conveyed smoothly to the composite tube without applying any local concentrated load. This was important to prohibit damaging of the tube at the gripping locations or during applying torsional load. The following preparations were done to perform the test:

- Two steel bars were manufactured having outer diameter equal to the inner diameter of the composite tube and they were inserted at the tube ends with small interference force. A through hole was performed at each end of the tube specimen passing through the split rings, composite tube, and the solid bars, as shown in Fig. 5.

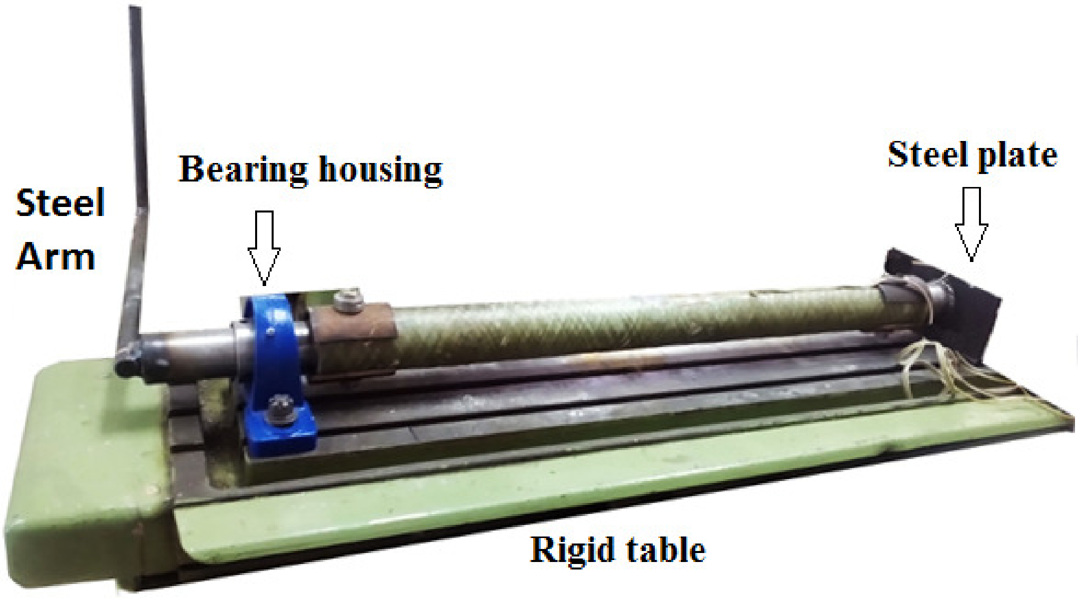


Fig. 4. Test rig set up for pure torsion.

- The tube was fixed on a leveled rigid table via a steel plate at one end and a bearing housing at the other end.
- The fixed plate was welded to the steel bar at one end of the tube, preventing its rotation. While the other steel bar was inserted inside the bearing house, permitting its free rotation under the applied torque at this end.
- A steel arm of 560mm length was welded to the steel bar, inserted inside the bearing. This arm was carrying the needed dead weights for applying the required torque.

The torque was conveyed through the bolt bearing areas, the sleeves contact area with the tube outer surface, and the contact area of the steel bar with inner surface of the tube. Hence, the torque was conveyed to the tube through a large contact area, preserving it damage under large concentrated loads.

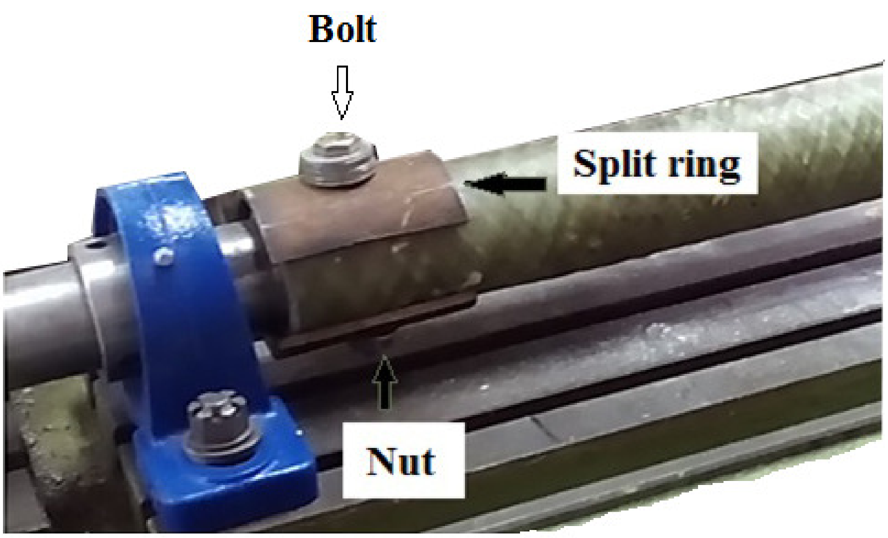


Fig. 5. Installation of the split ring on the tube' outer surface.

RUNNING OF THE TORSION TEST

The main goal of this test is to evaluate the torsional stiffness of thick-walled composite tubes. To get this aim, the generated strains on the outer surface of the used specimen will be measured. There are different methods to measure strains accurately. The most commonly used one is mounting electric resistance strain gauges at the concerned positions. The used strain gauge was **HBM** strain gauge **type RY81-6/120 rosette** which was specified to measure the normal strains located at angles +45/0/-45^o relative to the tubular specimen axis. The lead wires were connected to the **data acquisition system (DAQ)** which consisted of the following components:

- A portable Compact DAQ, 4-channels, Bridge, AI module type NI 9237 of **National Instruments Corporation**, with USB slot chassis carrier.
- Four quarter-bridge completion accessories (120 Ohm) connecting the strain gauges to the measuring module via **(RJ50)** cables, as shown in Fig. 6.
- A laptop with installed NI Max software version 14.0.

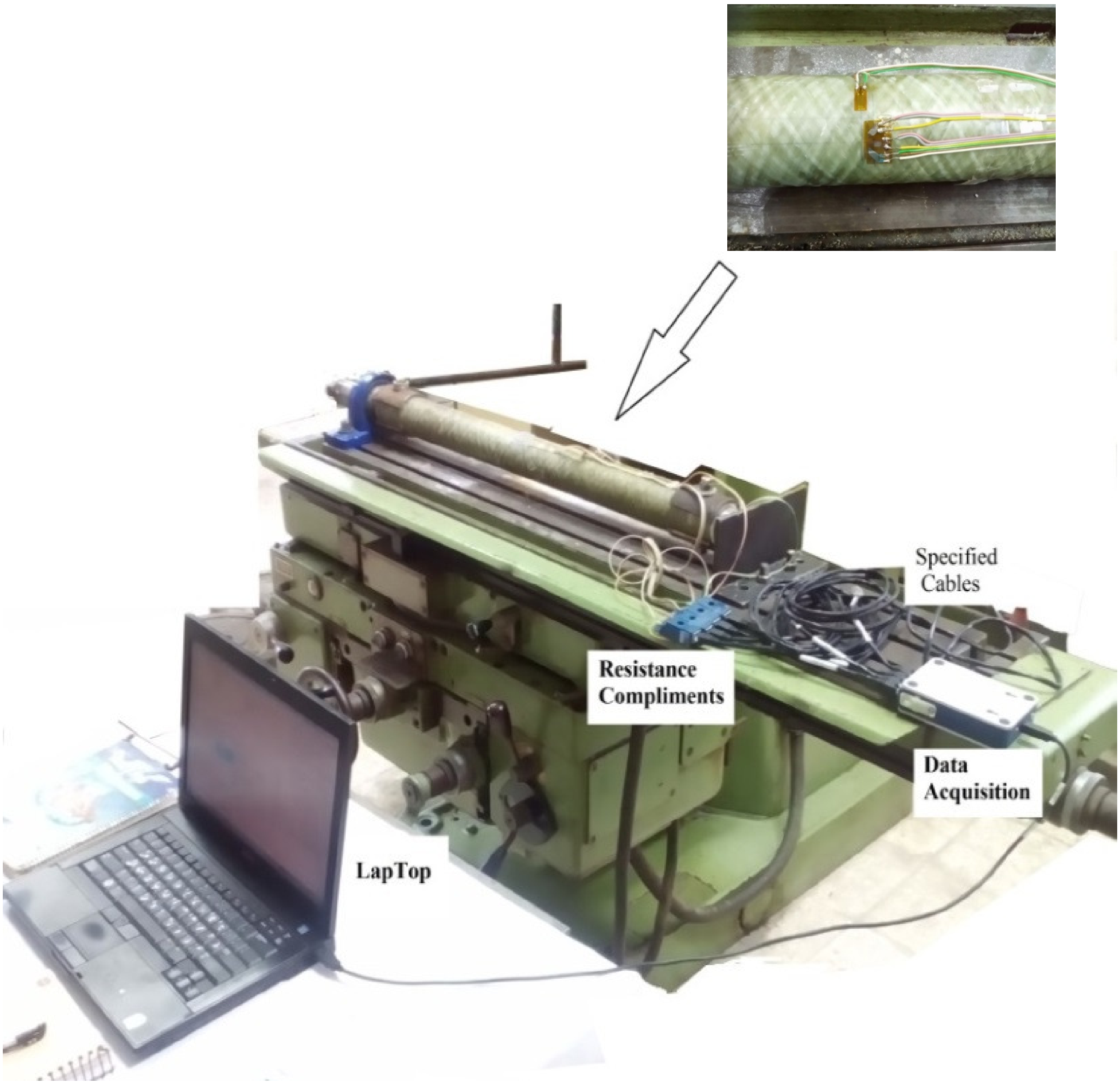


Fig. 6. Schematic of the strain measurement system.

The required torque was generated by putting different dead weights on the arm, as illustrated in Fig. 7. The shear strains were not measured directly, because the electrical resistance gauges were sensitive to normal strains only and cannot respond to shear strains. So, the shear strains (γ_{xy}) can be calculated from the measured normal strains ε_a, ε_b, and ε_c,where a=45°, b=0°, and c=-45°, using the following equations [9]:

$$\varepsilon_a = \varepsilon_x cos^2\theta_a + \varepsilon_y sin^2\theta_a + \gamma_{xy} cos\theta_a . sin\theta_a \tag{5}$$

$$\varepsilon_b = \varepsilon_x cos^2\theta_b + \varepsilon_y sin^2\theta_b + \gamma_{xy} cos\theta_b . sin\theta_b \tag{6}$$

$$\varepsilon_c = \varepsilon_x cos^2\theta_c + \varepsilon_y sin^2\theta_c + \gamma_{xy} cos\theta_c . sin\theta_c \tag{7}$$

The x, y coordinates represents direction of the tube axis and transverse (lateral) direction, respectively.

Fig. 7. Applying the dead weights to generate the required torques.

Form the last three equations, the unknown normal strains (ε_x, ε_y) and shear strain (γ_{xy}) can be calculated.

Referring to Eqn. (1), the torsional stiffness of the composite tube (GJ) is calculated taking into account the axial-torsional coupling parameter (B_{12}), such that:

$$GJ= (T- B_{12}.\varepsilon_x) \frac{r}{\gamma_{xy}} \tag{8}$$

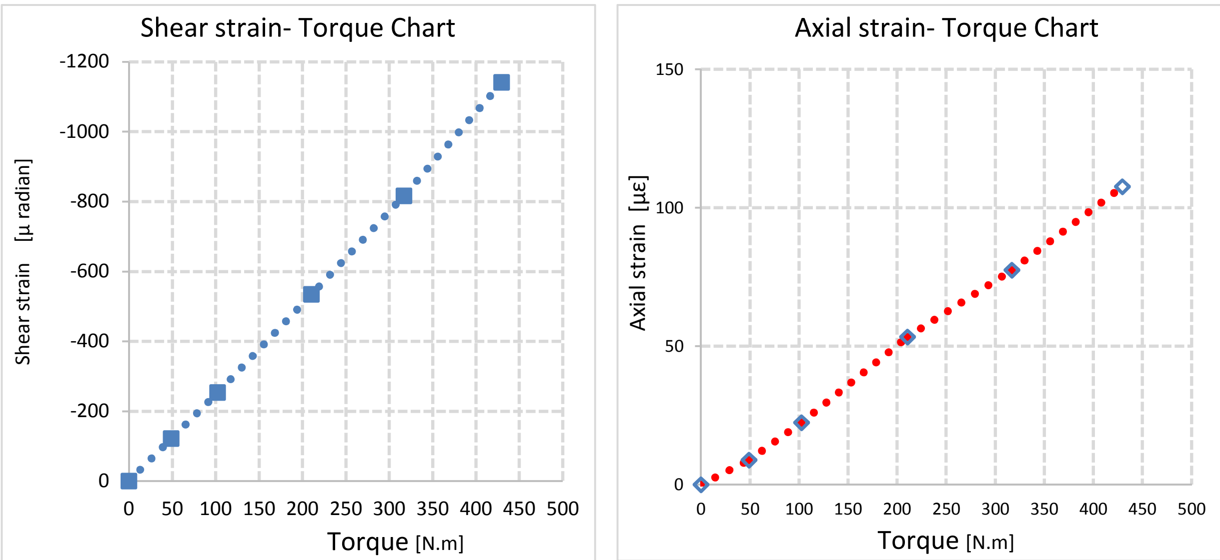
(B_{12}) is calculated from the theoretical solution of Ref. [2].

RESULTS AND DISCUSSIONS

By introducing the value of angles θ_a, θ_b, and θ_c , to be (+45°),(0°), and (-45°), respectively, and the average measured arbitrary strains ε_a, ε_b, and ε_c, into Eqns. (5), (6), and (7), one can calculate both the axial strains and shear strains on the outer surface of the specimen for every applied torque. The measured normal strains ε_{+45^o}, ε_{0^o}, and ε_{-45^o} are presented in Table 4. The experimental results for the applied torque (T) with the generated shear strain ($\boldsymbol{\gamma_{xy}}$) and the axial strain (ε_x) are plotted in Fig.8. It is shown from the Table 4 and figure (8) that the torsional moment generates a positive axial strain (ε_x), and a negative shear strain (γ_{xy}). Both of them increase as the applied torque increases. This is due to existing of coupling parameter (B_{12}).

Table 4. Strain gauge measurements.

Weight (N)	Torque (N.m)	$\boldsymbol{\varepsilon_a}$(+45°) (μ$\boldsymbol{\varepsilon}$)	$\boldsymbol{\varepsilon_b}$(0°) (μ$\boldsymbol{\varepsilon}$)	$\boldsymbol{\varepsilon_c}$(-45°) (μ$\boldsymbol{\varepsilon}$)
89	49	-61	9	59
186	102	-125	22	127
383	210	-260	53	272
577	317	-401	77	414
782	430	-563	108	576



(a) (b)

Fig. 8. (a) Shear and (b) axial strains against the applied torque.

By employing the analytical solution for axisymmetric loading, presented in Ref. [1], the value of (B_{12}) is obtained to be (1948.8 N.m). This value is used in Eqn. (8) to get the tube torsion stiffness (GJ). The average result of (GJ) is compared with that predicted using the analytical methods presented in Refs. [2] and [4].

The comparison is presented in Table 5; good agreement is generally obtained.

Table 5. Torsional stiffness comparison.

	Analytical solution [2]	Closed Form equation [4]	Average experimental Result
GJ ($N.m^2$)	13503	13500	12615
Error%	6.6%	6.6%	

Also, one can note the appeared peculiar behavior of the composite tube under torsion; that despite the tube is made of a balanced laminate of [θ/-θ] configuration; there exist a nonzero value of (B_{12}). The effect of this coupling parameter is illustrated in Fig. 8b, when one observes the generation of axial strain from a pure torsional load. This is because of the curved nature of the laminate in composite tubes with circular cross section, which makes the cross-section geometry of the outer lamina of (θ) orientation is slightly larger than that of the inner one oriented at (-θ). This nature makes the laminate to behave differently from the balanced one. One can also note that the generated axial strain is numerically too small compared to the corresponding shear strain. This can appear when comparing the value of the tube torsional stiffness to that of (B_{12}). Due to this result, one can make a good approximation by cancelling ($B_{12}.\varepsilon_x$) term in Eqn. (8) and (GJ) is found to be equal to 12609. So, one gets an accurate value for the torsional stiffness, directly from the measured data only, with no need to calculate (B_{12}) theoretically.

In the next section, the compression test of the tube is presented to confirm the existence of the shown axial-torsional coupling, and to measure the axial stiffness of the tube.

AXIAL COMPRESSION TEST

A compression test was carried out on the tubular specimen. The test was performed using a servo-hydraulic test machine, supplied from (MTS) Systems Corporation, placed at The Military Technical College. To avoid the slip of the tube during the axial compression test, two steel end fittings were manufactured to be inserted at the ends of the composite tube as shown in Fig. 9.

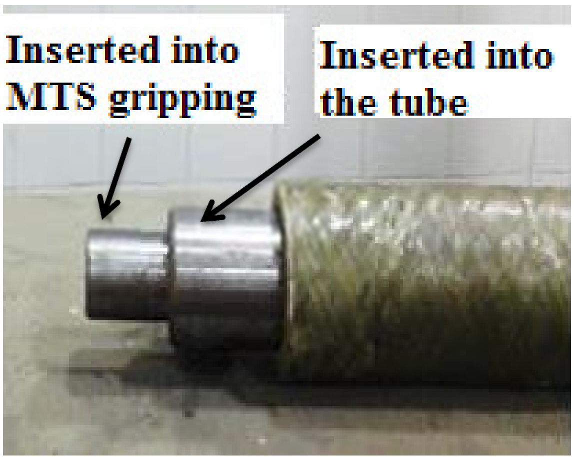


Fig. 9. Steel fitting ends.

Fig.10 shows the specimen with the steel fitting fixed in the machine grips. The tube is subjected to controlled compression loads from 5kN to 25kN. The normal strains are measured at (+45°), (0°), (-45°) form the tube axis using the strain gauges. The measured results are listed in Table 6. The generated axial strain ($\boldsymbol{\varepsilon_x}$) and shear strain ($\boldsymbol{\gamma_{xy}}$) are calculated from the above measured strains using Eqns. (5), (6), and (7).

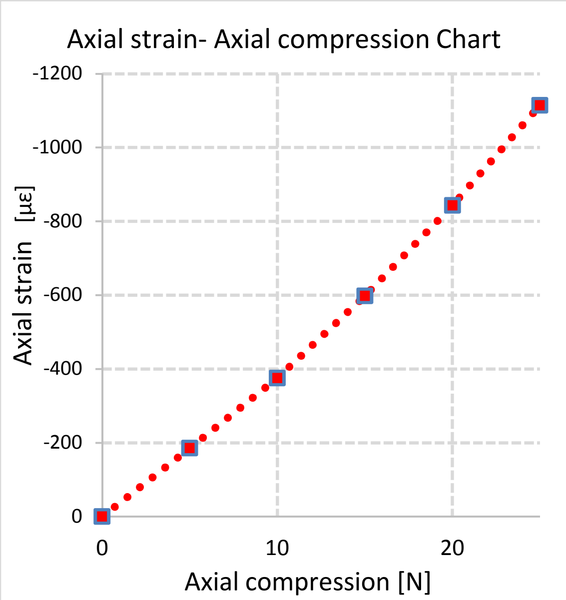
Fig.10. Axial compression test using MTS machine.

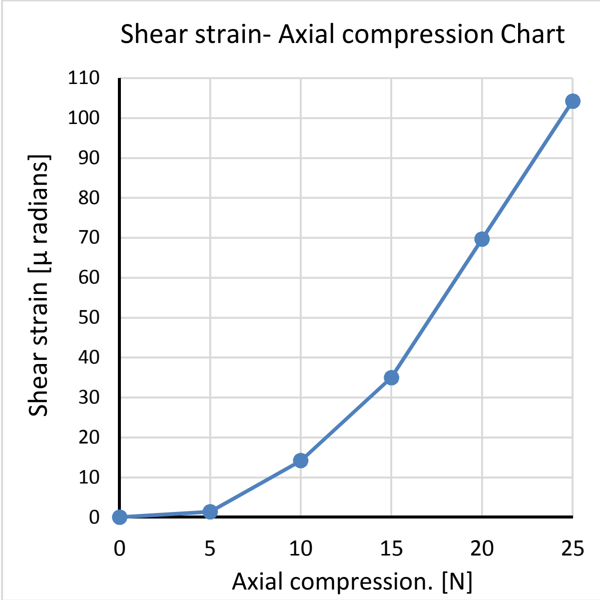
Table 6. Measured strain values in the axial compression test.

Loads (kN)	$\varepsilon_{45}{}^{o}$ (με)	$\varepsilon_{0}{}^{o}$ (με)	$\varepsilon_{-45}{}^{o}$ (με)
5	-62	-185	-60
10	-122	-375	-136
15	-193	-598	-228
20	-263	-843	-333
25	-342	-1114	-447

The results are plotted in Fig. 11. As the case of torsion test, the axial compression loading on the tube generated a positive shear strain (γ_{xy}) and a negative axial strain (ε_x). Their values increase as the axial load increases. The extensional stiffness of the composite tube (EA) can be obtained experimentally, utilizing the same theoretical value of B_{12} to be (1948.8 N.m) in the following equation obtained from Eqn(1) [2]:

$$EA = \left(P - B_{12}\frac{\gamma_{xy}}{r}\right)\frac{1}{\varepsilon_x} \tag{9}$$





(a) (b)

Fig. 11. Axial (a) and shear (b) strains against the applied compression force.

The average experimental result of EA is obtained and it is compared with the theoretical solution of Ref. [2] as shown in Table 7.

Table 7. Comparison of extensional stiffness results based on measurements with that of Ref. [2].

	Analytical solution [2]	Average experimental result
EA (kN)	28711.5	24178
Error%	11.2%	--

The good agreement between experimental and theoretical results of (EA) confirms the accuracy of the theoretical solution presented in Ref. [2], emphasizing its suitability for the analysis of thin and thick-walled composite tubes. It is also important to note that, the presented results support the outcomes of the torsion test for the axial–torsional coupling parameter. Therefore, a good result for (EA) can be obtained directly from the experimental results by cancelling (B_{12}) term in Eqn. (8). In addition, (EA) was found to be equal to (24980kN) directly from the experimental measurements with only 3.3% difference from calculated (EA) when using (B_{12}).

CONCLUSION

- The designed test rig for pure torsion succeeded to convey the torsional load to the composite tube smoothly with no damage at the gripping positions. This is because of the large contact areas which distribute the loading instead of being concentrated at a certain location.

- The average value of the torsional stiffness, obtained from the test, validates both the theoretical solution of Ref. [2], and the closed form equation of Ref. [4].

- The measured axial stiffness also validates the theoretical solution of Ref. [2].

- The curved nature of the tube laminate is found to have a nonzero value of the axial-torsional coupling parameter (B_{12}) even when the tube has a balanced laminate configuration.

- The numerical value of (B_{12}) is found to be small enough and it can be canceled for the composite tube of balanced laminate. This helps in measuring accurately both the torsional and axial stiffnesses of the tube directly from the results of experimental tests.

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