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Research Article

Experimental examination of the axial compression conduct of filament-wound cylindrical composite tubes at different wall thicknesses and orientation angles

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ABSTRACT

This study presents the results of experimental research on the behavior and stretching of hollow cylindrical epoxy tubes made of glass, carbon, and kevlar fibers subjected to axial compression load. Hollow cylindrical tubes were fabricated by fiber winding method using glass, carbon, and kevlar fiber-reinforced composite materials. In this study, hollow cylindrical composite tubes with constant outer (Ø17 millimeters), two different inner diameters (Ø12 and Ø13 millimeters; 2 ve 2,5 millimeters wall thickness), and 80 millimeters in height. Experimental research was carried out for two dissimilar wall thicknesses and four fiber orientation angles. The compressive strengths of all samples were investigated experimentally by applying loads in the axial direction. Twenty-four configurations of composite specimens were fabricated (three reinforcement materials, four winding angles, and two wall thicknesses) to research the impact of axial compression stress. Experimental results revealed that polymer reinforcement material, fiber winding angle, and wall thickness have a significant impact on the compressive stress of cylindrical composite tubes as a result of applied load in the axial direction. The conclusions show that the compressive stress of all reinforcement rises as the orientation angle and wall thickness increase under an axial compression load, and the compressive stress reaches a maximum when the orientation angle is 90° under an axial compression load. It was observed that the axial compressive stress was highest in glass/epoxy samples with 217 MPa, followed by carbon/epoxy samples with 173 MPa and kevlar/epoxy samples with 145 MPa, respectively. The axial compressive stress of all samples was highest at a 90° orientation angle and lowest at a 15° orientation angle. were found to have low values. It was observed that the axial compressive stress value increased in all reinforcement materials as the wall thickness increased.

Introduction

Composite materials design variability besides different material combinations, have high specific strength and make them highly appropriate to meet the different requirements of aerospace, defense industry, automobile, construction, marine, infrastructure, and sports products or electric motors. In many engineering fields, composite materials are preferred over conventional materials due to their superior properties such as high conductivity, rigidity, lightness, and thermal and corrosion resistance. These tubes can be better designed by varying the winding angle to meet the desired performance requirements. Composite tubes began to replace metal products in many engineering applications. Great emphasis was placed on the production and testing of composite tubes with different methods. There is a substantial amount of published data on the response of composite tubes to axial compression. Fiber winding is one of the composite production methods with relatively higher capacity and automation and lower production costs. It is mainly used in the manufacture of axisymmetric composite products such as tubes, ships, and domes used in the aerospace, military, and defense industries. The fiber winding method is widely used in the manufacture of axisymmetric composite parts such as tubes, shafts, pipes, and cylinders [1]. In recent years, many scientists have researched these superior materials and presented many scientific publications on these subjects for the use of industry and researchers. Zhangxiang P., et al. [2] numerically investigated the effects of braid angle and manufacturing errors on compression properties of three-dimensional (3D) carbon fiber/epoxy resin circular braided composite tubes. Compressed properties include initial modulus, compressive strength, failure stress, and both intact and defective damage propagation of composite models. According to the finite element analysis, it was observed that the compression properties decreased with the increase of the knitting angle and the error content. It has been observed that the braid angle, random errors in reinforcement, and resin have a great influence on the compression behavior of the three-dimensional (3D) braided composite pipe. Gang Z., Liqiu Z., [3] et al. experimentally investigated the local deterioration and harm mechanism under the effect of transverse low velocity of triaxial braided composite pipes with axial threads at dissimilar amounts and locations. In situ and real-time defect modes of composite tubes transversal low-speed impact, a new perspective has been successfully studied using high-velocity thermal imaging technology to capture the progressive damage behavior of composite structures during a temporary case. Yang W., [4] et al. analyzed the multiaxial mechanical conduct of orderly Kelvin and Octet-B closed-cell suds. The impacts on the stress-strain reaction, defect mode, and first yield behavior of the two suds, as well as their related density, were investigated by comparing them. It was observed that under compression-shear loading at 15° and 30°, the deterioration features of both foams were quite like compared to those of single-axis compression. Hilburger et al. [5] analyzed 24 dissimilar types of bamboo composite tube groups, 6 groups circumferentially and 18 groups longitudinally under axial compression. The load-displacement curves, stress-strain relation, and defect modes of bamboo composite tubes were researched. The impacts of dissimilar factors such as diameter, wrapping layers, length-to-diameter ratio, and fiber winding on the mechanical features of bamboo composite tubes were analyzed. It was sighted that the top tension of the longitudinal bamboo composite tubes was influenced by the number of wrapping layers in the bamboo segment. Jia X, et al. [6] analyzed the behavior of rectangular bore composite cylindrical shells beneath axial compression. The impacts of the laminate properties and hollow dimension of the hollow composite shell on the axial compression behavior were researched. It was analyzed that the response under axial compression is severely affected by the inner load dispersion near the bores and regional displacements. It was observed that the inner load dispersions and regional displacements are affected by the material properties, the dimension of the bores, and the defects in the skin. Ochelski and Gotowicki [7] analyzed the impact of the geometric factor and the orientation angle on the crushing behavior of the CFRP cylinder and found that the compressive modulus, compressive strength, and crack length diminished with the rise of the orientation angle. Curtis S., et al. [8] investigated the energy absorption talent of conical tubes made of glass-epoxy and carbon-epoxy composites. They observed that the environmentally oriented fibers in the specimens had a crucial impact on increasing energy absorption and decreasing the number of interlayer cracks. Kim J-S, et al. [9] have researched the influence of penetration exposure on the damage formation, deterioration, and strength of filament-wrapping composite tubes. They compared the static penetration and low-velocity impact results. Azeem M., et al. [10] compared the axial crushing reactions of cylindrical composite tubes reinforced with carbon/Kevlar hybrid woven fabrics. The results indicated that the specific energy absorption (SEA) of the interlayer hybrid structures was at smaller yields than that of carbon fiber reinforced polymer (CFRP) and Kevlar. Nevertheless, the post-crush integrity of carbon fiber-reinforced polymer (CFRP) tubes can be improved, as simply a minor quantity of fiber waste is created during crushing. Majid and Krishnan et al. [11,12] analyzed the impact of wrapping angle on the glass/epoxy composite tubes exposed to multiaxial cyclical loading. The authors established the distinct ring-to-axial stress ratios using the indicated angles: ±45˚, ±55˚, and ±63˚. The resulting stress-strain relationship revealed a strong dependence between the wrap angle and strain ratio. The composite pipe advantage in particular is corrosive resistant so good used to transport corrosive fluids [13]. Carbon Fiber Reinforced Plastic (CFRP) has the advantages of high specific modulus, high specific strength, wide damping ratio, and fatigue resistance. A hollow shaft made of CFRP is particularly appropriate for long-span, high rotational speed transmission systems and large torque [14, 15]. Abu Talib et al. [16] improved a finite element analysis model to analyze the composite transmission shaft and observed the impacts of stacking sequence and winding angle on the crucial bending velocity. Babamohammadi et al. [17] studied an analysis of the mechanical characterization of the fiber-reinforced hollow circle based on a three-dimensional (3D) shell model noting only in-plane stress. Mirzaei et al. [18] summarized experimentally and analytically the behavior of aluminum/epoxy hybrid circular tubes exposed to quasi-static axial compression loads. They established that the stacking sequence had a significant impact. It was observed that the tubes obtained as hybrid absorbed more than three times the tubes obtained from aluminum. Nan et al. [19] different lengths of CFRP cylindrical shells with an outer diameter of 20 mm and a wall thickness of 1 mm produced by pultrusion used in axial compression tests. The stiffness, ultimate strength, and medium-scale failure modes of the cylindrical shells were determined. Adin H. et al. [20] numerically investigated the fatigue behavior of composite patched and unpatched Al 5083 aluminum sheets. They applied the Finite Element Method for numerical work. As a result of the numerical study, they determined that the highest fatigue life (1593,2 N) was in the 30° angled "V" notched and patched sample. They emphasized that the contribution of the composite patch is very important. Adin H. et al. [21] numerically investigated the fatigue behavior of unpatched and patched aluminum pipes. They used the Finite Element Method for fatigue analysis in their work. As a result of the numerical study, it was determined that patch size is an effective parameter of fatigue strength and that quarter-circle and semi-circle composite patches increase fatigue life. Adin H. et al. [22] studied the mechanical properties of composite materials produced from woven jute. Samples produced according to ASTM D procedures were subjected to tensile and three-point bending loads. They found that the tensile and bending fracture loads of the composite materials obtained by using particle-reinforced adhesive increased. Adhesive joints are increasingly used in the marine, construction, automotive, and aerospace industries due to their low cost and lightweight, ease of application compared to traditional joining methods such as soldering, rivets, welding, and bolts [23].

In this study, hollow cylindrical composite tubes have different inner diameters of 12, and 13 millimeters with constant outer diameters of 17 millimeters and 80-millimeter height were used. All specimens were manufactured at four different orientation angles by filament winding machine. Glass, carbon, and kevlar fibers were used as reinforcement material and epoxy resin was used as matrix material. The axial compressive stresses of the samples were calculated theoretically using Equation (1). The axial compressive loads of the samples were obtained from the test device experimentally. The obtained axial compressive stress was compared depending on reinforcement materials, orientation angle, and wall thickness.

Materials and Methods

Materials and Geometry

The specimens used in the experiments were manufactured at the Izoreel Composite Inc., İzmir, Türkiye. In this study for hollow cylindrical composite tubes the reinforcement material used is glass, carbon and kevlar fibers, and Araldite MY 740 epoxy resin matrix with HY 918 hardener. A mixture of epoxy resin and hardener at a ratio of 100:25 was used as the adhesive. Polymerization is carried out at 80°C for 5 hours then 130°C for 15 hours. The mechanical and physical features of the composite fibers used in production are given in Table 1. The inner diameters of the tubes were 12 and 13 mm, while their wall thicknesses varied from 2 to 2.5 mm. Hollow cylindrical composite tubes with two different inner (D_{inner}=12 and 13 millimeters) and constant outer diameters (D_{outer}=17 millimeter) and H=80-millimeter height were used (Figure 2).

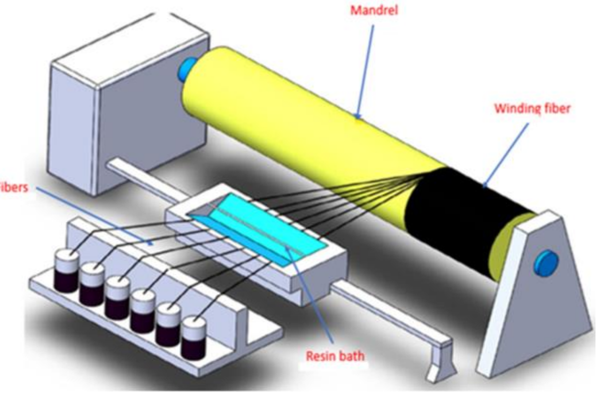


Figure 1. Filament winding process of hollow cylindrical tubes

a b c

Figure 2. Test specimens of a) glass/epoxy, b) carbon/epoxy, c) kevlar /epoxy

Table 1. Shear modulus values, fiber volume, and Poisson’s ratio of glass/epoxy, carbon/epoxy, and kevlar/epoxy composite materials

Materials	Shear modulus (G) MPa	Poisson’s ratio υ	Fiber volumetric fraction $\%V_f$
Glass/epoxy	7100	0,30	45
Carbon/epoxy	4760	0,27	67
Kevlar/epoxy	3580	0,23	86

Experimental studies

Test Setup

Before starting each test, the upper and lower jaws were positioned to contact the upper and lower surfaces of the specimen under test, respectively. During the axial compression test, the upper jaw was moved downward at a constant speed while the lower jaw of the test machine was held static/stationary. The machine’s computerized data acquisition system automatically recorded the loading values.

The height and outer diameter of the hollow cylindrical composite specimens were kept constant for all three reinforcement materials (Figure 3). For axial compression tests, AG-X SHIMADZU universal tensile tester with 250 kN capacity shown in Figure. 4 was used. The loading speed was taken as 1mm.min^{-1} in all experiments. All tests were repeated three times for consistency (Figure 4). All experiments were performed at a test speed of 1mm.min^{-1} and at room temperature. According to ASTM D 695 standard, axial compressive stress was obtained from Equation (1) by applying an axial force to all specimens after being placed between two supports, lower jaw fixed and upper jaw movable All hollow cylindrical composite tubes were tested until failure (Figure 5-7).

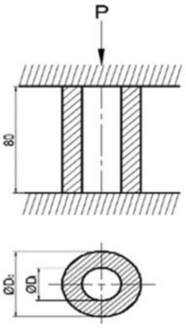
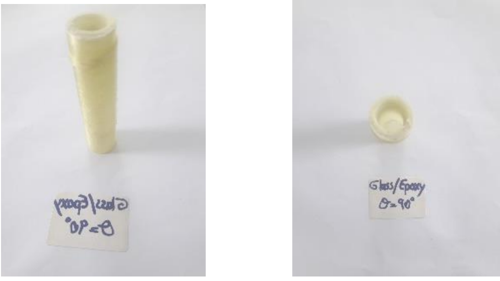


Figure 3. Schematic of test samples

Figure 4. Test setup for the axial compression



a b

Figure 5. Damage formation of glass/epoxy specimen under axial compression load; a) front view, b) top view

a b

Figure 6. Damage formation of carbon/epoxy specimen under axial compression load; a) front view, b) top view

a b

Figure 7. Damage formation of kevlar/epoxy specimen under axial compression load; a) front view, b) top view

$$\sigma=\frac{P_{max}}{A} \tag{1}$$

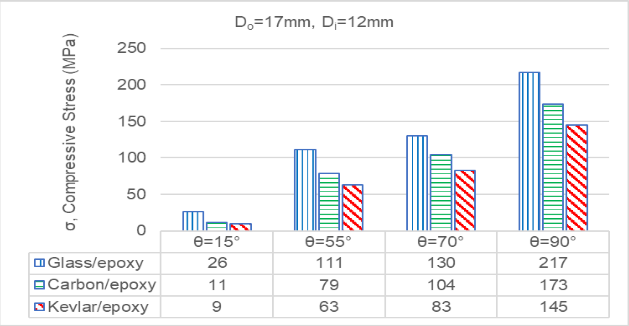
$$A=\pi\,\frac{D_o^2-D_i^2}{4} \tag{2}$$

Results and discussion

Influences of reinforcement materials on axial compressive stress

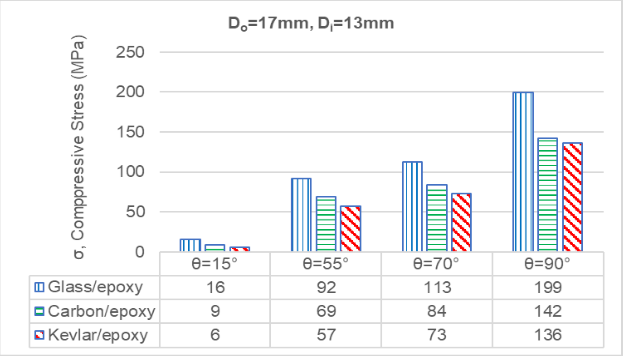
In this section, the results of quasi-static axial compression tests performed on composite tubes produced using different reinforcing materials, winding angles, and wall thicknesses are classified, presented, and discussed. The effect of strengthening composite tubes with glass, carbon, and kevlar, and changing the wall thickness and fiber winding angle on the quasi-static axial compressive stress was investigated in detail.

This study, it is aimed to investigate the variation of the axial compressive stress values obtained experimentally and the relationship between the reinforcement materials. Figures 8 and 9 consist of experimentally obtained axial compressive stress and orientation angle curves, taking into account the effect of the reinforcement material. The highest axial compressive stress values obtained in the whole orientation angle were observed to occur in glass/epoxy, carbon/epoxy, and kevlar/epoxy specimens, respectively, when Figures 8 and 9 were examined together. In other words, it was understood that the axial compressive stress value of the glass/epoxy specimens obtained according to Equation (1) was higher than the others. It was determined that kevlar/epoxy specimens had the lowest axial compressive stress values obtained.



	θ=15°	θ=55°	θ=70°	θ=90°
◫ Glass/epoxy	26	111	130	217
▤ Carbon/epoxy	11	79	104	173
▨ Kevlar/epoxy	9	63	83	145

Figure 8. Compressive stress-reinforcement materials curve



	θ=15°	θ=55°	θ=70°	θ=90°
◫ Glass/epoxy	16	92	113	199
▤ Carbon/epoxy	9	69	84	142
▨ Kevlar/epoxy	6	57	73	136

Figure 9. Compressive stress-reinforcement materials curve

Influences of orientation angle on axial compressive stress

The effect of the orientation angle on axial compressive stress values obtained from the test device experimentally was examined together with Figures 10 and 11. Accordingly, it was observed that the axial compressive stress values obtained experimentally increased in glass/epoxy, carbon/epoxy, and kevlar/epoxy specimens as the orientation angle increased. It was seen that the highest axial compressive stress values obtained for all reinforcement materials were obtained at an orientation angle of 90° and the smallest at an orientation angle of 15°. It was observed that the axial compressive stress obtained for all three reinforcement materials and both inner diameters increased approximately two times when the orientation angle reached 90°. It was determined that the axial compressive stress values obtained in the four orientation angles (15°, 55°, 70°, 90°) were close to each other, and this value increased more sharply than the others at the 90° orientation angle for all reinforcement materials. It was concluded that by placing the fibers vertically (at a 90° orientation angle), the maximum load should be applied to all specimens for axial compression damage to occur. It was observed that increasing the fiber-winding angle from 15° to 90° increased axial compressive stress.

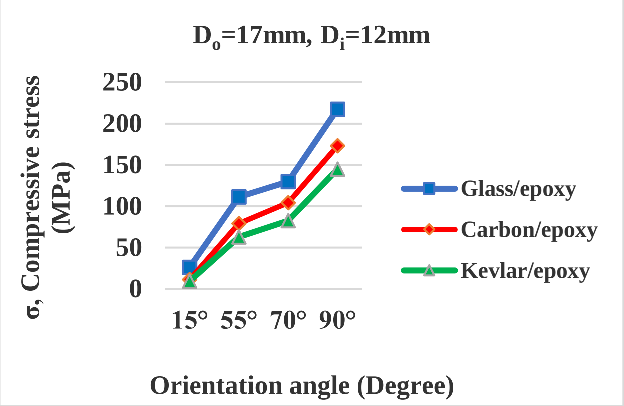


Figure 10. Compressive stress-orientation angle curve

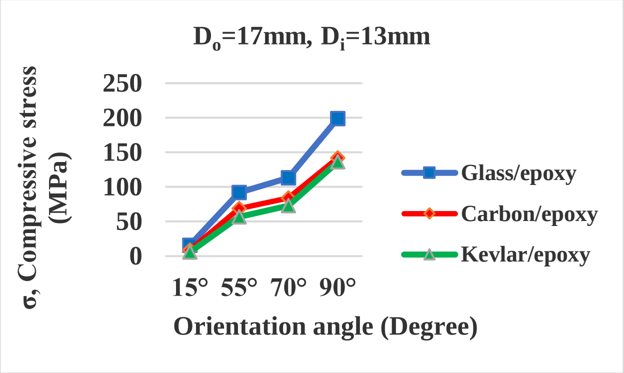
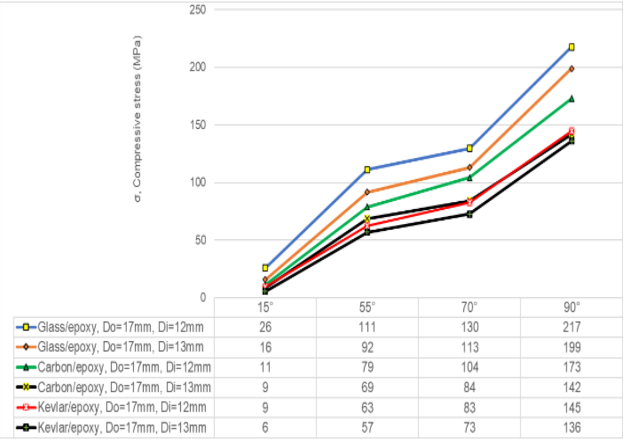


Figure 11. Compressive stress-orientation angle curve

Influences of wall-thickness on axial compressive stress

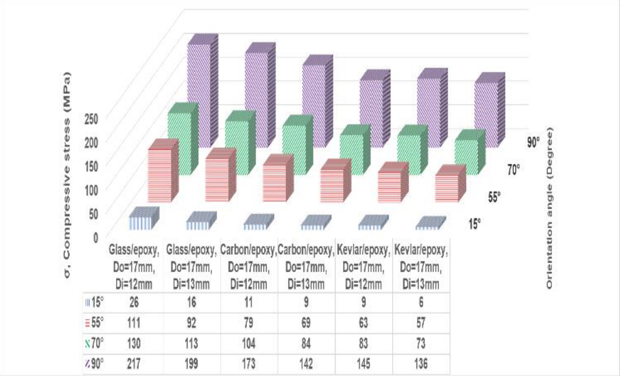
Figures 12 and 13 show the variation of the axial compressive stress values at all orientation angles of the reinforcement materials according to the wall thickness. As seen in Figures 12 and 13, it was observed that the axial compressive stress at all orientation angles increased as the wall thickness increased. It was found that the highest axial compressive stress occurred in all reinforcement materials with both 12- and 13-millimeter inner diameters, glass/epoxy, carbon/epoxy, and kevlar/epoxy specimens at 90° orientation angle, respectively. Similarly, it was determined that the smallest axial compressive stress was at the 15° orientation angle in all reinforcement materials, in kevlar/epoxy, carbon/epoxy, and glass/epoxy specimens, respectively. Here, too, it was determined that the axial compressive stress at a 90° orientation angle increased approximately 2,5 times compared to the 15° orientation angle for all reinforcement materials. In addition, as the orientation angle increased, it was observed that the axial compressive stress of all reinforcement materials increased in both 12- and 13-millimeter inner diameters.

When Figures 12 and 13 are examined together, it is concluded that the effect of the wall thickness on the axial compressive stress is quite significant. As can be seen from these graphs, it was determined that the axial compressive stress increased as the wall thickness of the specimens increased.



	15°	55°	70°	90°
Glass/epoxy, Do=17mm, Di=12mm	26	111	130	217
Glass/epoxy, Do=17mm, Di=13mm	16	92	113	199
Carbon/epoxy, Do=17mm, Di=12mm	11	79	104	173
Carbon/epoxy, Do=17mm, Di=13mm	9	69	84	142
Kevlar/epoxy, Do=17mm, Di=12mm	9	63	83	145
Kevlar/epoxy, Do=17mm, Di=13mm	6	57	73	136

Figure 12. Influences of wall-thickness on axial compressive stress



	Glass/epoxy, Do=17mm, Di=12mm	Glass/epoxy, Do=17mm, Di=13mm	Carbon/epoxy, Do=17mm, Di=12mm	Carbon/epoxy, Do=17mm, Di=13mm	Kevlar/epoxy, Do=17mm, Di=12mm	Kevlar/epoxy, Do=17mm, Di=13mm
15°	26	16	11	9	9	6
55°	111	92	79	69	63	57
70°	130	113	104	84	83	73
90°	217	199	173	142	145	136

Figure 13. Influences of wall-thickness on axial compressive stress

Conclusions

In this study, hollow cylindrical composite tubes have different inner diameters of 12, and 13 millimeters with constant outer diameters of 17 millimeters and 80-millimeter height were used. All specimens were manufactured at four different orientation angles by filament winding machine. Glass, carbon, and kevlar fibers were used as reinforcement material and epoxy resin was used as matrix material in hollow cylindrical composite tubes. The axial compressive stresses of the specimens were calculated theoretically using Equation (1). The axial compressive stress of the specimens was obtained from the test device experimentally. The obtained axial compressive stress was compared depending on reinforcement materials, orientation angle, and wall thickness.

The conclusions drawn from this study can be summarized as follows:

1. It was determined that the use of different reinforcement materials had significant effects on axial compressive stress. It was observed that the axial compressive stress was highest in glass/epoxy samples with 217 MPa, followed by carbon/epoxy samples with 173 MPa and kevlar/epoxy samples with 145 MPa, respectively.
2. It was understood that the orientation angle has a significant influence on the axial compressive stress experimentally. It was found that the axial compressive stress increased with increasing orientation angle. It was determined that the axial compressive stress and orientation angle of all specimens had the highest values at 90° and the lowest values at 15°. In addition, it was observed that the axial compressive stress at all orientation angles was the best in glass/epoxy specimens.
3. It was understood that the wall thickness has a significant influence on the axial compressive stress in hollow cylindrical composite tubes. It was observed that the axial compressive stress increased as the wall thickness increased.

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