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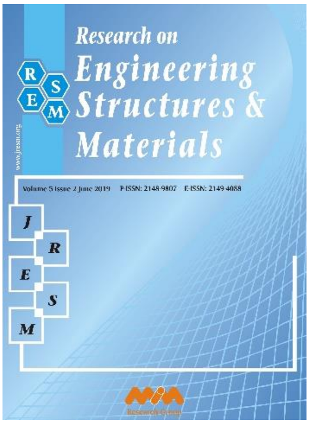

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Research Article

Comparison of the compression characteristics of 2D braided and circular knitted carbon/epoxy composite tubes

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Abstract

Two-(biaxial and triaxial) and three-dimensional braided fabric structures are generally used as structural components in various industries such as ballistic, aerospace, automotive, energy, medical, marine, construction, and sports applications. Due to the advantages of braided structures like high level of uniformity, near net-shape manufacturing, design flexibility, repairability, low manufacturing cost, and damage resistance capability, braiding process have been preferred widely in the manufacturing of composite products.
This study reports the influence of the braiding angle on the compression behaviour of carbon/epoxy tubular composites manufactured based on 2D biaxial braided fabrics, and also their comparison with that of the circular knitted ones. In order to determine the effect of braiding angle, 2D biaxial braids were manufactured by using three different braiding angles (62°, 67°, and 75°). Composite tube specimens were manufactured by vacuum bagging technique and their compression tests were performed. The results imply that braided carbon/epoxy tubes could be more suitable for the cases requiring smaller deformation and higher compressive stresses when compared to the circular knitted ones.

1. Introduction

Braiding is defined as a textile process of intertwining at least three parallel strands (or yarns) of fibre in order to manufacture narrow fabrics like cords and ropes with non-orthogonal fibre orientation, or in order to cover (overbraid) some profiles [1, 2]. In their simplest form, braids consist of single layers of yarns that are diagonally interlaced by moving supply packages around one another, typically by horn gears [3]. The principal difference between the braided and other fabric-processing methods such as weaving and knitting is that woven fabrics are formed by orthogonal interlacing of yarns while knitted fabrics are formed by inter-looping yarns, whereas conventional braiding forms non-orthogonal, multidirectional (typically, two- or three-directional) fabrics without any loops [1]. Braids can be linear products (ropes), curved or plane shell, or solid structures (one, two or three-dimensional fabrics) with constant or variable cross-section, and have closed or open appearance [2]. Braided structures are characterized by bias yarn orientation, and are defined, according to the German Industry Standard DIN 60000, as 2D or 3D fabrics with even thread density and closed fabric appearance. The threads are aligned in the radial direction in a 2D braid, whereas fibres are oriented in through-thickness direction in 3D braids [4]. 2D braiding methods such as sleeve braiding and round braiding are primarily used for textile applications like the production of cords, ropes, or simple cord braids. They can also be used for reinforcement

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purposes in special applications. More complex structures become feasible by 3D-braiding methods. These methods are mainly used for the production of three-dimensional reinforcement structures for lightweight construction [5].

Due to its easy production, which does not involve yarn preparatory processes, braids are one of the most cost-effective production methods. From natural fibres such as cotton, silk, wool, and linen, to regenerated and synthetic fibres, metallic fibres, all of yarn compositions can be easily converted into braided structures [6]. Two-(biaxial and triaxial) and three-dimensional braided fabric structures are generally used as structural components in various industries such as civil infrastructure, transportation, ballistic, aerospace and space, automotive, medical, and sports applications [6, 7].

Braiding process can also be preferred for the production of complex shapes with nonregular cross-sections (round, square, triangle, flat, etc.). The nonregular cross-section generates modification of the braiding angle on different areas of the part to be produced. Braiding angle, which is defined as the angle of the fibres with respect to the longitudinal 0 degree-axis, is the most important parameter that determines the cover factor of braided structure [8] (Fig. 1). This angle can be between 1° and 89°, but is usually in the range of 30°–80° in practice [2, 9]. It is closely related to process parameters such as the braid diameter, the take-up speed, and the rotational speed of the carriers [8]. A low carrier speed with a higher take-up speed results in loose braided structures with low braiding angles, which consequently have a low cover factor. But, high carrier speed and low take-up speed result in closely packed braided structures having higher braiding angles and better cover factors [6].

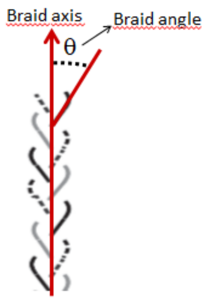


Fig. 1. Braid angle.

Due to the high level of uniformity, near net-shape manufacturing, applicability of a very wide range of shapes, design flexibility, repairability, low manufacturing cost, minimum material waste, and damage resistance capability of braided structures, braiding process have been widely employed in the production of composites [10]. Braided composites that are one type of composite material distinguished by their inter-woven structure are fibrous composite materials that consist of long fibres impregnated by a matrix. Braided composites are defined as angle-ply composites and characterized by the alignment of their yarns that are interlaced diagonally about an axis [11]. Change in this braiding angle parameter will in turn change reinforcement properties of the resulting composite product. Wall thickness, weight fraction or fibre volume fraction, reinforcement angle are some properties of the produced composite that will be affected.

Braiding technique allows continuous production of composite products having variable cross-section, arbitrary shapes, custom material property, custom yarn patterning, and hybrid reinforcement. Biaxial and triaxial reinforcements are achievable by this manufacturing method. Typical examples of braided composite products are aircraft frame [12], engine bleed valve duct, satellite structure parts, scaffolds for articular cartilage [13] and fighter inlet duct [14], propeller blade for turboprop planes [15], field hockey stick [16], and tubes with different shapes and variable cross-sections. Other continuous composite profile production techniques comparable to braiding are filament winding and pultrusion. Filament winding is widespread known for biaxial reinforcements, while pultrusion yields unidirectionally (UD) reinforced composites with constant cross-section. Some example composite products for filament winding are large diameter pipes, blades, and aeroplane fuselage. Pultrusion is well-known for composite profile products for construction industry especially, and smaller diameter pipes.

A considerable amount of literature has been published on braided composites. Rajesh et al. compared dynamic mechanical and free vibration behaviour of natural fibre braided fabric composites with conventional and knitted ones, and reported that the braided yarn fabric enhances the stiffness of the composite structure and hence results in higher natural frequencies while knitted fabric reinforcement enhances modal loss factor of the composite structure due the spiral orientation of yams and large gaps [17]. Rios-Soberanis et al. used textiles of different architecture to manufacture epoxy based composites in order to study failure events under tensile load by using acoustic emission technique which is a powerful characterization tool due to its link between acoustic emission data and fracture mechanics, which makes this relation a very useful from the engineering point of view [18]. Ma and Gao reviewed the development and features of three types of textile structures, including weaving, knitting, and braiding and described the impact tension behaviours and the damage mechanisms of textile structural composites [19]. Ren et al. compared the effectiveness of laminar composite z-directional microfiber reinforcement in improving fracture toughness with that of a 3-D braided 8-layer glass fibre preform/epoxy composite plate. The results showed that the Mode I fracture toughness (G(l)) of the 3-D braided preform reinforced composites are about 10 times of the 2-D layered glass fabric laminar composites [20]. Goyal et al. focused on 2 x 2 biaxial braided composites and developed three-dimensional finite element micromechanics models for two material systems: glass fibre/epoxy matrix and carbon fibre/epoxy matrix [21].

In this study, it is aimed to investigate the effect of the braiding angle on the compression behaviour of carbon/epoxy tubular composites manufactured based on 2D biaxial braided fabrics, and also their comparison with that of the circular knitted ones. In order to determine the effect of braiding angle, 2D biaxial braids were manufactured by using three different braiding angles (62°, 67°, and 75°). Composite tube specimens were manufactured by vacuum bagging technique, and their compression tests were performed.

2. Material and Method

2.1. Material

Carbon 3K yarns (AKSAca, Turkey) were used in the production of braided and circular knitted structures. These yarns were preferred due to their thickness, easy processability and availability in the market. The characteristics of the yarns are listed in Table 1.

Table 1. The characteristics of the Carbon 3K yarns

Property	
Tensile strength	3800 MPa
Tensile modulus	240 GPa
Strain	1.6 %
Density	1.78 g/cm^3
Yield	200 g/1000m
Sizing type & amount	1.0-1.5 %

2.2 Braiding Process

Biaxial 2D braided carbon structures were produced by using a laboratory type braiding machine having 48 spools. Yarns were wound on spools by a winding machine. Carriers move spools in opposite directions along a circular path. Yarn ends are fixed on a mandrel and interlace as shown in Fig. 2. Interlaced yarns move through the convergence zone of the machine, towards the mandrel, which takes the fabric up the loom. The yarns follow helical paths on the mandrel and interlace each time the spools meet [22]. Braiding over Teflon release film coated mandrels allowed the introduction of curvature in the reinforcement without cutting the yarns. In order to determine the effect of braid angle, three different braid angles (62°, 67°, and 75°) were chosen during braiding process.

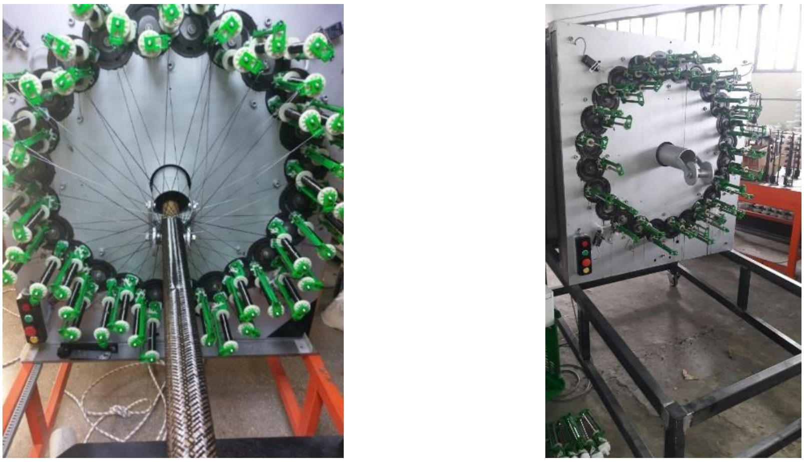


Fig. 2. 2D braiding machine

2.3 Knitting Process

A mechanical single jersey circular knitting machine CKM 01, Faycon (İpekçioğlu Makine, Turkey) was used for the production of circular knitted fabrics (Fig. 3). Carbon fibres were knitted into a circular knitted tube in a single jersey weave pattern [23].

Fig. 3. Mechanical single jersey circular knitting machine.

2.4 Carbon/Epoxy Tube Production

The resin mixture was prepared by mixing KL674A epoxy resin and KL674B hardener in a ratio of 60:40 parts by weight respectively. Resin amount used was calculated by 2:1 weight ratio to the fibres. Two layers of the knitted sock were stretched along the length of the tube and tightly slid onto the iron bar tube with a diameter of 50 mm, to get a thickness of 1.5 mm. Then the structures were vacuum infused (Fig. 4). Similarly, for braided tube production, carbon fibre braided mandrels having a diameter of 50 mm were vacuum infused, again with a 2:1 resin/fibre weight ratio.

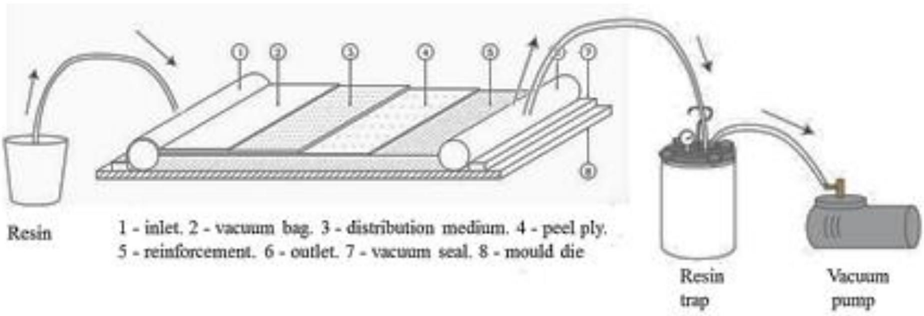


Fig. 4. Typical vacuum infusion lay-up components [23]

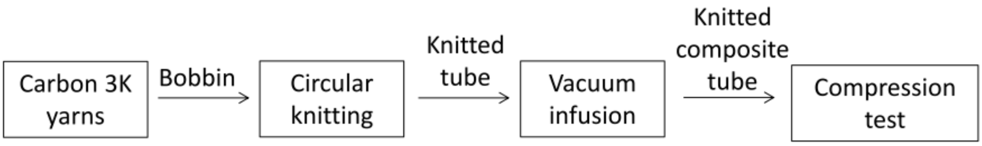
The resin mixture was kept in the pot. A transparent plastic tube was dipped into the resin pot and connected to the inlet stuck on the tube. The tube was wrapped in a plastic bag with ends sealed and the rubber hose (outlet) from the waste pot was connected to vacuum so that the resin is drawn through the length of the tube wetting all the sections uniformly. After the resin had wetted out the entire tube length, it was cured at room temperature for 24 hours. After cooling, the cured tube was removed from the iron bar by sliding out.

2.5 Compression Testing

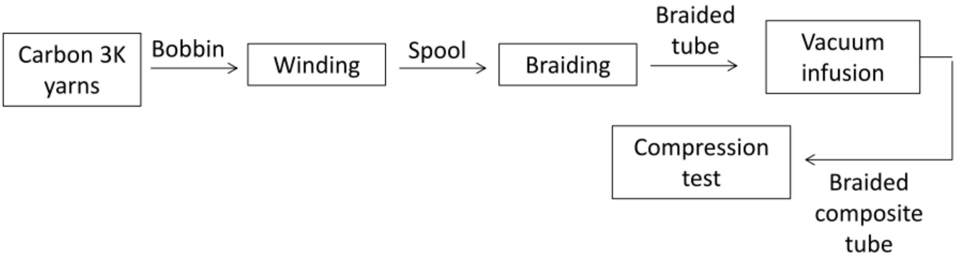
Axial compression tests [24] were conducted on 50 mm long composite tube specimens using a Shimadzu AGIS universal tester equipped with a 100 kN compression apparatus (Fig. 5). Cross-head speed was held constant at 0.033 m/s. Wall thickness values of the composite tubes, which are required for compressive stress calculations, were measured using a digital calliper (Mitutoyo).

(a) (b)

Fig. 5. Universal tension-compression tester (a) and compression testing of tubes (b)



(a)



(b)

Fig. 6. Methodology of the experiments for the circular knitted composite tubes (a), and the braided composite tubes (b).

3. Results and Discussions

Measured wall thickness values and compression test results of the circular knitted and the three different braided carbon/epoxy tubes are given in Table 2.

Table 2. Compression test data of carbon/epoxy tubes

Property	Knitted	62° braided	67° braided	75° braided
Wall thickness [mm]	1.5	0.45	0.52	0.67
Compression load [N]	3461±108	1514±108	1809±455	4711±707
Compressive stress [MPa]	14.3±0.5	22.6±1.6	23.1±4.0	47.6±8.1

Figure 7 shows a typical stress-strain curve for the compression test results of knitted carbon/epoxy composite tubes. A typical deformed specimen shape is also attached in the figure. The specimens experienced diamond shaped buckling, and then returned to their initial shapes some period after the tests.

Typical compressive behaviours of braided carbon/epoxy composite tubes are also given in Fig. 8. As can be compared from Table 2, increasing braiding angle changes the maximum stress value. This effect is in accordance with the diamond shaped buckling mode mentioned by Harte and Fleck, who state that there are four possible modes of buckling for braided circular tubes in axial compression: Fibre microbuckling, Diamond shaped buckling, Concertina buckling, and Euler buckling [24]. An example image for diamond shaped buckling mode occurring in the specimens can be seen in Fig. 9. The specimens returned to their initial shapes shortly just after the tests.

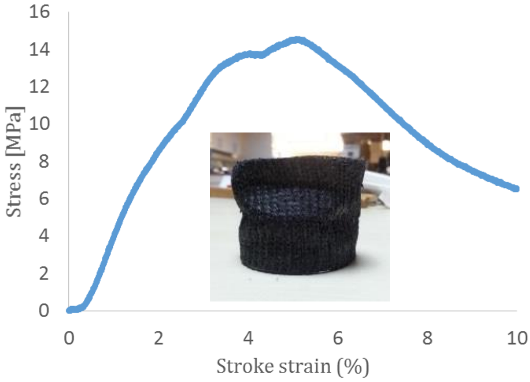


Fig. 7. Typical stress-strain graph for the compression test of knitted tubes.

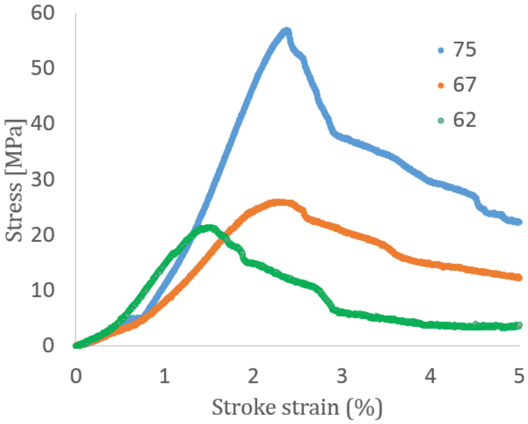


Fig. 8. Typical stress-strain graphs for the compression tests of braided tubes.

When Table 2 is examined, it is clearly seen that wall thickness changes by braiding angle, which in turn affects the compressive stress value of the tube. Knitted tube bears high load, but in expense of having higher wall thickness, which in turn counts for more cost. This allows one to be able to apply only low stress values to these tubes. As they have a highly curved yarn structure, they have low structural strength [25]. When compared to knitted ones, load values that can be carried are smaller for 62° and 67° braided tubes. But, because of their thinner walls, they can bear higher compressive stresses. Contrarily, in the case of 75° braided tube, compression load is higher than the knitted one although its wall thickness is about 2.2 times smaller.

Another outcome is that the strain at maximum stress value is smaller for the braided tubes than that of the knitted ones. Additionally, load value settles at higher strain values for the knitted tubes when compared to the braided ones.

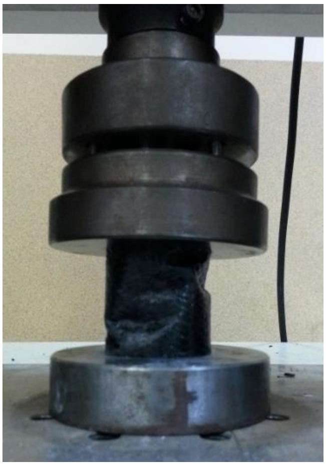


Fig. 9. Diamond shaped buckling of braided tubes during compression testing.

4. Conclusion

Carbon/epoxy tubular composites were successfully manufactured based on 2D biaxial braided fabrics and circular knitted fabrics. Three different braiding angles (62°, 67°, and 75°) were investigated. Compression test results of the composites were analysed. From the results of this study, the following conclusions can be drawn:

- When compressive load was applied, all specimens experienced diamond shaped buckling. This was expected as a consequence of the chosen length/diameter ratio of approximately 1:1. The braided tube composites returned to their original shape immediately after unloading while the knitted tube could recover to its initial shape after a much longer time.
- Braiding technique ended up in thinner tubes when compared to circular knitting. Braided tubes with 62°, 67°, and 75° braiding angle resulted in wall thickness values of 0.45, 0.52, and 0.67 mm, respectively. This was caused by the decrease in the take-up speed. On the other hand, circular knitted tubes had a wall thickness of 1.5 mm. This value is approximately 3.3, 2.9, and 2.2 folds when compared to the case of braided tubes.
- Thinner tubes obtained in case of braiding technique will obviously result in lighter composite structures when compared to the case of knitting technique. This will also reduce the material costs together with transportation, storage, ease of handling, etc.
- When compared to the knitted ones, thinner structures that were obtained by braiding experienced higher compressive stress values as a matter of course. Although the circular knitted tube beared higher load when compared to 62° and 67° braided tubes, it experienced less compressive stress. On the other hand, 75° braided tube could bear higher load even than that of the knitted one despite its thinner wall thickness.
- Knitted tube structure had a higher failure strain or deformation range compared to that of the braided ones.
- The strain at maximum stress is smaller for the braided tubes than that of the knitted ones. Increase in braiding angle seems to increase this strain value, which seems to approach a limit for high braiding angles.
- Load value (Compression stress) settles at higher strain values for the knitted tubes when compared to the braided ones.

- The results imply that braided carbon/epoxy tubes could be more suitable for smaller deformation cases with high compressive stress when compared to the knitted composite tubes.
- Future studies may be conducted for additional braiding angle values. Compression loads/stresses can be analysed as a function of varying cross-sections or wall thickness values.

Acknowledgements

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