A Study of Quadriaxial and Triaxial Composite Tubes Developed by Braid-Winding

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1 Introduction

Cylindrical composite structures are used in a variety of applications in industries such as marine, offshore, aerospace, automotive, sports, civil engineering structures, machinery, tooling and so on. With the expansion of composite cylinders and tubes industries, research on composite tube has been increased with various aims. The studies include different fibre reinforcement techniques on different shapes, manufacturing flexibility, mechanical properties, optimization of different fabrication methods, matrix system and prediction of material properties using simulation. All of these studies are equally important for achieving the desired performance of tubes for particular applications. Fibre layup techniques have many variables to study for example fibre types, lay up architecture which includes crimp, interlacement, angle, fibre count etc. Layup techniques have significant effects on the ultimate properties of the structure since variation in fibre layup can change the mechanical properties of composite. In this research, attempts were made to study two methods of fibre reinforcements in combination for fabricating composite tubes.

Tubular composites have been fabricated using two dimensional (2D) braiding and filament winding. Winding in combination with braiding process was used to create a hybrid layup. Tensile and torsion tests have been carried out for both types of layups to measure strength and modulus of the tubes and observe the failure process. The aim of this paper is to present a study on fabricating quadriaxial braid-wound (QBW) hybrid layup and the subsequent composite’s behaviour under different types of loading.

2 Background

Continuous fibre layup techniques for composites fabrication employ processes widely used for textile manufacturing such as weaving, winding and braiding. Individually these processes have been studied and used for fabricating tubular structures. Filament winding (FW) is a frequently used method for pressure retaining structure reinforcement. In this method, generally filament tow is impregnated in a resin bath followed by winding under high tension on to a rotating mandrel. Precise lay down of fibres at high speed with the advantage of manufacturing large structures are the basis of filament winding being a significant method in the composite industry.[1]

Fabric wrapping around a tool is another common method for making cylindrical structures. A seamless multilayer wrapping process has been developed and the process is being used commercially for manufacturing composite tubular members.[2]

The 2D braiding is a method of developing a tubular biaxial sleeve by non-orthogonally interlaced fibres. An additional scope of incorporating axial fibres can produce a tri-axial structure which is necessary for composite structures loaded in the axial direction. The bias interlacement of the fibres in the braid structure provides high torsional resistance and tolerance to impact damage.[3] Braiding has a major advantage on filament winding in terms of higher structural integrity due to the presence of interlacement. Toughness and fatigue strength of braided composite is also better than that of filament wound composites.[4]

For studying FW pipes, fabricators often use a simple approach of netting analysis[5] for optimising fibre orientation. The analysis and the experiment show that the layup of ±55° is a favourable configuration for internal pressure loading for a closed end cylinder. In a study [6] on FW of pressure vessels with fibre orientations ranging between ±45° to ±55° were tested under biaxial test. The authors reported a maximum burst pressure for ±50° layup. The deviation from netting
analysis optimum angle was concluded to be due to a matrix contribution to the failure process. A recent study[7] applied a ‘genetic algorithm’ for optimising the hybrid high strength (HS) and high modulus (HM) carbon fibre made drive shafts. It suggests some general rules for fibre stacking with the necessity of fibre reinforcement in multiple directions. The ±45° HS carbon fibre layup was recommended considering the maximum torque direction, 0° HM fibre for increased axial stiffness and 90° HM fibre layup away from the centre to increase the torsional buckling torque.

Deciding an optimum fibre angle depends on the application of composites under consideration. Fibre reinforced composites have an advantage of tailoring the desired properties by placing the fibres during fabrication. However conventional FW has it’s limitation in placing fibres at 0° on a core maintaining the tension and avoiding the slippage. On the other hand, although a braid structure can be constructed with fibre angles up to 85°[4], the ±85° braid will generate higher fibre crimp which is not a desired property for manufacturing composite as higher crimp will lead to decrease in strength[8]. The respective limitations of both braiding and winding created a scope for combining both the lay up techniques to optimize the fabrication of preforms.

In order to study fabrication of QBW layup, a process hybrid of braiding and filament winding has been decided. The QBW layup has a quasi-isotropic architecture of ±45°/0°/90° (Fig. 1). Prior to fabricating QBW lay up, another quasi-isotropic layup of ±60°/0° has been produced with braiding to study the manufacturing of tubular structure along with its properties.

For QBW layup, apart from developing a quasi-isotropic architecture, the best utilization of winding was considered. In a study of multiple angle filament wound layup stacking sequence of tube, P. Mertiny et al.[9] observed differences in strength values. They explained that higher strength was achieved with an axial reinforcement placed in inner layers of the tube in case of hoop dominated loading. On the other hand for higher axial stress, the axial reinforcement were laid in upper layer[9]. Triaxial braid in multilayer has a phenomenon of nesting which is the degree of decrease in laminate thickness[10]. Nevertheless during filament winding, the fibre tension produces a compact structure itself.

Therefore hoop wound layers were preferred to be laid on outer layers of the laminate in order to consolidate the inner braid layers during preforming.

![Fig. 1 Braid-Wound layup (QBW) architecture](image)

### 3 Manufacturing

#### 3.1 Materials

For the purpose of manufacturing the tubes in this research, HS carbon fibre T700SC was used. The carbon tow consists of 12000 filaments (12K) of 7µm diameter with a linear density of 800 tex. The tensile strength of the fibre is 4900 MPa and tensile modulus is 230 GPa. The fibre was impregnated with epoxy resin Araldite LY564 with hardener XB3486. The resin and hardener mixing ratio was 100:34.

#### 3.2 Braiding

Braiding was carried out by using a 2D, 48 carrier braiding machine (Fig. 2) with a capacity of 24 axial yarn deposition. Triaxial braid (TB) structures of 2X2 interlacement were produced for both TB and QBW layup on to a metal tube that was used as an inner tool. For TB tubes seven layers of braid with ±60°/0° orientation was laid on to the mandrel. Between each layers the mandrel position was changed to facilitate the distribution of axial yarns over the circumference and the free end of the braid was secured. A single layer of braid developed a thickness of 0.54 mm. Subsequently the addition of other layers the stack thickness reduced up to 18% due to nesting producing a structure with dry stack thickness of 3.1 mm. The average bias orientation of the fibre was 60.5±0.4°. Fibre amount laid in each bias and axial direction is approximately 40% and 20% by weight respectively.
3.3 Braid-Winding

Conventional filament winding equipment comprises a traversing fibre delivery system which is synchronized with the rotating mandrel. The filament winding was carried out for this research using a newly developed winding machine. Unlike conventional winding, this machine has a rotating winding wheel which can deliver the filaments from multiple delivery units placed on to the wheel. The mandrel has a traversing motion through the centre of the wheel. The linear motion of the mandrel is synchronized with the rotating unit; in consequence the machine can control the filament angle on the mandrel.

Braid-winding of QBW structure was carried out in two different steps. On the first step triaxial layup of $\pm 45^\circ/0^\circ$ was completed by using braiding. The average bias orientation was $46 \pm 0.7^\circ$. Five layers of braid were placed onto the mandrel constructing a stack thickness of 1.95 mm and the decrease in total thickness because of nesting was approximately 21%. Following the braiding, four layers of fibres were wound onto the braid and the average angle was 85.4$ \pm $ 0.5$^\circ$ (Fig. 3). A single layer of fibre wound consisted of four tows delivered from the winding wheel. The amount of fibre deposited in individual bias, axial and hoop direction was approximately 26%, 17% and 31% by weight respectively. These amounts comply with the minimum requirement of fibre is each direction for a quasi-isotropic layup which is 12.5% [11].

Individual tow tension was 10$ \pm $0.5 N and four tows were used to wind a single layer. Addition of one layer winding brought the total laminate thickness down to 1.79 mm consolidating the braid structure. Finally, with four layers of winding, the dry thickness of QBW layup was 2.27 mm.

3.4 Resin infusion and curing

For wetting the dry fibres the vacuum assisted resin infusion (VARI) technique was preferred to resin transfer moulding (RTM). In an attempt to use RTM method, an outer mould was designed. The space between the outer and inner moulds defined the composite wall thickness. Consequently fewer fibre layers were laid to achieve similar thickness compared to VARI method resulting in a lower fibre to resin ratio. In addition to that, mechanical clamping of outer moulds applies pressure only on the concentrated areas especially when parts of multiple pieces of outer mould with curvature are fastened. VARI provides a uniform pressure of 100 kPa externally on to the entire surface of the part to achieve a consolidated structure.

During preparation for VARI, in different layers release fabric and resin transfer mesh was wrapped around the circumference with minimum overlap. After placing the vacuum and resin distribution lines at opposite ends of the core tool the vacuum bag was placed around the arrangement. The edges of the bag were closed using sealant tape to provide an airtight seal. After drawing the vacuum inside the envelope, the inlet tube was opened to let the resin flow (Fig. 4). The resin flow was controlled manually using a clamp to ensure a slow wetting of the fibre.

Following the resin infusion, the part was cured at 80$^\circ$C for 8 hours. After the curing cycle had completed, the temperature was reduced very slowly.
to cool the part down in about 6 hours. The vacuum bag and other materials aiding the VARI process was then removed which was followed by removing the composite tube (Fig. 5 a) from the inner tool.

The specimen length for all tests was 140 mm with 101±1 mm gauge length when mounted on the test fixture. In order to measure the strain, electric strain gauge rosettes were placed in the centre of the gauge length. Each rosettes had three strain gauges placed at an orientation of 0°/45°/90° for tensile test specimen and -45°/0°/+45° for torsion test specimen, in both cases 0° being parallel to the tube axis. Three rosettes were mounted on the tube outer circumference 120° from each other for tensile test, whereas two rosettes were placed on to the tube 180° apart from each other for torsion test. The specimens were mounted onto the test fixtures using structural adhesive that was cured at 55°C for 3 hours. After curing the adhesive the assembly was cooled down to the standard laboratory environment. The strain gauges were connected to a cartridge that was later connected to the data recording instrument Schlumberger Orion during the test.

4 Testing
4.1 Specimen details and preparation

The test specimens of both QBW and TB type had an average inner diameter of 101.8 mm with wall thickness 1.9±0.3 mm and 2.1±0.3 mm respectively. Consolidation during VARI and curing reduced 1 mm of the TB laminate thickness whereas the reduction in thickness was 0.4 mm for QBW layup. Despite having a dry laminate thickness variation of 0.83 mm, QBW tube formed a wall thickness with 0.2 mm variation to that of TB tube. It shows that a considerable amount of consolidation occurred at the preform stage. Fiber volume fraction (FVF) was measured using the matrix digestion method according to the standard ASTM D3171. The FVF of QBW and TB structures were 62.3±1.3% and 61.4±0.4% respectively. The specimens had void fractions as low as 0.01% for both types.

Table 1 Composite physical properties and Consolidation details

<table>
<thead>
<tr>
<th>Layup</th>
<th>(±45°/0°)\textgreek{g}/90°4 (QBW)</th>
<th>(±60°/0°)\textgreek{g}/ (TB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total preform thickness (mm)</td>
<td>2.27</td>
<td>3.1</td>
</tr>
<tr>
<td>Composite thickness (mm)</td>
<td>1.9±0.3</td>
<td>2.1±0.3</td>
</tr>
<tr>
<td>Thickness reduction (%)</td>
<td>16%</td>
<td>32%</td>
</tr>
<tr>
<td>FVF (%)</td>
<td>62.3±1.3</td>
<td>61.4±0.4</td>
</tr>
</tbody>
</table>

4.2 Tensile test

The composite tube specimens were tested under tensile loading. The test was conducted following the standard ASTM D5450. As shown in Fig. 6 a, the specimens were tested in a hydraulically actuated 300 kN Instron 8802 testing equipment. The testing speed was controlled in terms of crosshead displacement of the machine which was kept constant to 1.3 mm/min. Strain measurement was carried out in two methods simultaneously. Alongside strain recording from strain gauge, a photogrammetric method was employed by using a Q-400 system of digital image correlation (DIC) developed by Dantec Dynamics. The technique uses two cameras to record a speckle pattern painted on the surface of the specimen and analysis software ISTRA 4D. This software was used to recognize a speckle pattern painted on the exterior surface of the specimen. During deformation of the specimen, the
Q-400 system determines the position of the pattern therefore the specimen face with respect to a reference image taken after the calibration of the system. The software tracks three dimensional displacements of points within the region of focus. For this study due to the colour bleeding of the speckle pattern, the 3D images were not complete (Fig. 6 b). However the images showed the test specimen deformations on the surface with different colours correspond to the range of strain and the required data at every step was collected effectively.

![Image](image.png)

Fig. 6 (a) Tensile test of a QBW type tube showing strain gauges and DIC speckle pattern (b) Initial 3D image reconstruction by DIC software showing incomplete image with gaps on the surface

### 4.3 Torsion test

The specimens were tested under torsion loading following the standard ASTM D 5448. The specimens were tested in servo-hydraulic Instron 8802 tension/torsion equipment with a torque capacity of 1000 N-m. As the specimen was mounted on the machine, the rotational member was kept free to move axially to avoid axial force generation during the test. A rotation rate of 2°/min was kept constant while the strain data was recorded using the data logger.

### 5 Results and analysis

#### 5.1 Tensile test

Both TB and QBW specimens were tested under tensile loading and ultimate tensile strength (UTS) values were calculated from the maximum load and the cross sectional area. The ultimate strength of TB and QBW tubes were 385.4 MPa and 355.4 MPa respectively. It is apparent that the presence of higher number of axial fibre in the TB specimen than that in QBW specimen resulted in higher tensile strength. In contrast despite having 28% less axial fibres in QBW structure, the strength difference is about 8% compared to TB structures. One of the major factors that compensated the loss in strength due to the lack of axial reinforcement was assumed to be the alignment of bias fibres, the arrangement of those were close to the axis of loading.

The average principal strains for both axial and circumferential directions were calculated separately from each strain gauge rosettes and then the average value was used. The tensile stress-strain graph along with tensile stress-circumferential strain graph for both types of tube is shown in Fig. 6. Tensile moduli of elasticity for the tubes were 29.9 GPa and 37.6 GPa corresponding to TB and QBW tube specimens. Although TB structure had higher UTS, the modulus is about 20% less than that of QBW structure. This difference in modulus can be explained with the fibre architectural difference. The presence of 45° braid fibres in QBW layup which resisted higher deformation to increasing load in contrast to TB layup. Higher strain against the stress of TB specimen compared to that of QBW specimen can also be observed from the stress-strain plot shown in Fig. 7. Between 150 and 200 MPa the tensile stress-strain graph for QBW specimen shows drops in strain while the specimen keeps carrying the load which can be considered as noise caused by internal crack formation. Beyond the point of 214.9 MPa stress, the graph for QBW was discontinued due to the failure of the strain gauge which is explained in the following section. Poisson’s ratio for the TB tube was 0.24 whereas the ratio is 0.4 for hybrid QBW layup composite tube.

During the tensile test of QBW tube, layers of the composite structure had gone through different extension. The load was acting in the transverse direction to the hoop wound fibres, therefore the top four FW layers had a different behaviour than the braided layers laid inside. In the Fig. 9, on the stress strain graph, surface strain images from DIC have been shown at different stress values. It appears that about 60% of the ultimate stress strain drop along the direction of hoop yarns (Fig. 9 a) which can be explained as the matrix cracks within the filament wound layers created by the accumulation of local damage. This process was appeared noticeably between 215-230 MPa in the DIC image (Fig. 9 b).
The image also shows the region with higher strain that lies between the low strain sections created by the cracks. Due to the high strain the hoop layers started to split transversely within the FW layer. With the increase in load, sound of internal fracture was heard at the same time which eventually appeared later as band splitting. The transverse cracks on the outer hoop layers started to fracture the top FW layers in ‘band spiral’ failure mode (Fig. 11 b). During this splitting event, the de-bonding between the split bands and the inner braid structure took place. The de-bonded FW layer lies completely separate from the disintegrated braid layers which was observed from the optical image (Fig. 12 a) of the tube wall. On the other hand, image of TB type tube (Fig. 8) shows complete delamination on the fractured surface. Occurrence of splitting disrupted the comprehensive strain measurement of the QBW structure by damaging the strain gauges. The fractured outer surface of the QBW tube caused breakdown of strain gauges therefore it wasn’t possible to obtain failure strain. The load-extension data was recorded simultaneously by the Instron software (Bluehill v.2) which was not taken into consideration as the data was not solely representative of the composite specimen. However during the test, the load-extension graph generated by Bluehill showed the uninterrupted increase in load. This explains that despite split in the FW hoop layers, the braid laminated composite continued to take the load. As the stress was increased from 200 MPa onwards the layer splitting event caused damage of the structure on the tube wall. The layer split exposed the underlying braid interface hence left the DIC equipment to measure the displacement of the surface focused with some area uncovered by the speckle pattern. DIC images however showed the influence of braid fibres over the complete structure during the test.

Images from surface strain measurement shows strain build up along the bias oriented fibres for TB structure (Fig. 10 b) creating the diamond pattern of the braid architecture. From this observation, fibre crossover points (dotted circled in Fig. 10a) as well as the area in the middle of a unit cell (dotted circle in Fig. 10 b) can be identified. Fig. 10(a) shows the DIC image of the specimen at about 305 MPa. At this stage it is apparent that the interlacing points in the braid structure went under high strain when the rest of the area remained within the medium range of strain. Just before the specimen failed at 385 MPa stress, at about 380 MPa, the top section of the specimen was highly strained (global strain 1.35%) which can be observed from DIC image in Fig. 10 b. The specimen failed at that high strain region. Under the tensile load, after interfacial de-bonding, bias fibres from the braid construction tend to straighten themselves at first from the waviness caused by crimp. This phenomenon is followed by the braided bias fibres lying next to the inner wall moving out of the interior of the tube (Fig. 12 b). This movement from one set of bias fibre caused the other set running in the opposite direction being split at the interlacing point. In the damaged region, all the axial fibres were found to be ruptured along the length while the bias fibres were mostly split across the width of the tow as shown in Fig. 12(c).

![Fig. 7 Stress-strain graph for TB and QBW type tube](image7)

![Fig. 8 Triaxially Braided tube specimen after the tensile test showing entirely delaminated wall cross section](image8)
Fig. 10DIC images of Triaxially braided (TB) specimen (a) At about 305 MPa the image shows high strain at fibre interlacing point (global strain 1.14%).

Fig. 9 Surface strain images of quadriaxial braid-wound tube under tensile loading shown alongside Stress-Global strain graph. (a) Image taken at about 60% of the UTS shows strain drops along the hoop fibre orientation as well as corresponding high strain build up. (b) About 80% of UTS development of numerous cracks in the form of circumferential band on the tube surface with subsequent high and low strain region. (c) Specimen at about 90% of UTS showing cracked region with purple bands and elevated strain zone covering most of the surface.

(b) Strain on the bias fibres illustrating the form of braid unit cell (dotted diamond shape), dotted circled area shows the strain drop in the middle of unit cells due to matrix damage. At about 380 MPa (right before the specimen failed at 385 MPa) high strain (global strain 1.35%) formation in line (shown with dotted arrow) shows the region where the specimen failed.
Table 2 Tensile test data summary

<table>
<thead>
<tr>
<th>Fibre layup tube code</th>
<th>Tensile strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
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<tbody>
<tr>
<td>(±45°/0°)_4/90°_4 (QBW)</td>
<td>355.4</td>
<td>37.6</td>
<td>0.4</td>
</tr>
<tr>
<td>(±60°/0°)_7 (TB)</td>
<td>385.4</td>
<td>29.9</td>
<td>0.24</td>
</tr>
</tbody>
</table>

5.2 Torsion test

The torque capacity was not adequate to load the specimens to reach the failure stress, yet the in plane shear modulus was calculated which is presented in the Table 3.

Table 3 Torsion test summary

<table>
<thead>
<tr>
<th>Fibre layup tube code</th>
<th>Shear Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(±45°/0°)_4/90°_4 (QBW)</td>
<td>16.8</td>
</tr>
<tr>
<td>(±60°/0°)_7 (TB)</td>
<td>20.1</td>
</tr>
</tbody>
</table>

6 Concluding remarks

In this study, a hybrid layup technique was used to manufacture a composite tube which was tested under tensile loading. The tube was compared with a tri-axially braided tube with a different layup that showed small increase in strength but the hybrid layup showed higher modulus. However, the failure mode under the tensile load of hybrid layup composite tube showed loss of structural integrity which led to a conclusion of avoiding the hoop layers on the edge of the inner or outer wall surface. Due to the presence of different amount of axial fibre reinforcement, the tensile strength result was not comparable to evaluate but observations made during and after the test were explained in the result and analysis section. A next stage of the current study is in progress in which the observations from this study have been considered in order to conduct a more comparable study. Further investigation has been planned to carry out the torsion test with higher torque capacity equipment.

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8 References


