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BRAID-WINDING FOR OPTIMUM TUBULAR PREFORMING

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ABSTRACT

The two-dimensional (2D) braiding and filament winding (FW) are widely used processes for tubular preform manufacturing for composite structures. However FW and braiding are incapable of longitudinal and hoop fibre reinforcement respectively. In order to take advantage of both the processes being used for tubular preforming, this study was carried out to associate the processes for inline manufacturing. Enhanced processibility was achieved as it allowed manufacturing of quadriaxial quasi-isotropic (QQ) (±45°/0°/90°) layup. The manufacturing capability of QQ configuration provided flexibility in tubular preform design. In addition, composite tubes developed by using 2D braiding and vacuum assisted resin infusion (VARI) often generate an imperfection called wrinkle. During the debulking process under compression, stress relaxation within the braid layers result in out of plane distortion creating wrinkles. Using the combined braid-winding processes the major causes of wrinkle formation, radius of curvature and fibre bulk was eliminated significantly reducing the possibility of wrinkle formation.

INTRODUCTION

Braiding and filament winding (FW) process has the versatility of developing a tubular preform for cylindrical composites. Both of these two processes can be used for preforming with fibre continuity between layers. The fundamental difference between the structures produced using braiding and FW lies in the preform structures. FW produces a non-interlaced preform, while braiding is usually used for developing interlaced structures. Braid structure with interlacement has the advantage of providing impact damage resistance[1] to the structure. In contrast FW provides unidirectional strength in the fibre direction[2] such as cylinders subjected to internal pressure. Together braiding and winding process are complementary and has the potential to be used for in-line preforming. The combination of both the processes can be justified from different aspects mainly from the mechanical properties. However this study presents the braid-winding process focusing on the influence of the layup combination on the improved tubular layup. Braid-winding is a two stage process in which the preform is developed in two distinct interlaced and non-interlaced layers. Therefore there is no fibre continuity between the layers. Tubular braided composite often produces a defect known as wrinkle during vacuum assisted manufacturing. However as a result of over-winding, braid structures become consolidated and the combined layup prevents development of wrinkle under vacuum. Simultaneously the process combination can offer the advantage of producing a quadriaxial quasi-isotropic layup for tubular preform.

DEVELOPMENT OF A QUADRIAXIAL QUASI-ISOTROPIC (QQ) STRUCTURE:

An optimum fibre orientation for a layup can be tailored according to the composite application. Braiding allows manufacturing quasi isotropic triaxial structure $(\pm60°/0°)_s$ however the layup is not best suitable for providing applications requiring hoop strength. Hence Quadriaxial Quasi-isotropic (QQ) structure $(\pm45°/0°/90°)_s$ is a suitable layup for providing simultaneous reinforcements for a structure under hoop, axial and torsion loading. Braid-winding allows developing a QQ structure although it is a two stage process. The process combination also allows alternative triaxial $(\pm30°/90°)_s$ braid-FW quasi-isotropic layup. Although this layup can be produced with non-crimp FW, it can be developed using biaxial braiding and hoop winding harnessing the benefits of both structures.

Triaxial braid and hoop winding can be carried out in consecutive layers for a QQ structure. Initially a non-symmetric overwound braid structure[3] $(\pm45°/0°)_5/90°_4$ was developed to understand the performance of the hybrid layup composite under tensile loading. The strain behaviour of the hoop wound stack of the wall was different than that of underlying braid stack. As a result the hoop layers had transverse cracks at ~60% of the ultimate tensile strength while the braid stack continued to take load. Taking into consideration of the premature failure of the hoop FW stack on braid, further studies were carried out on braid-FW structure where the FW layers were embedded in between braid layers. This approach also provided layup symmetry.

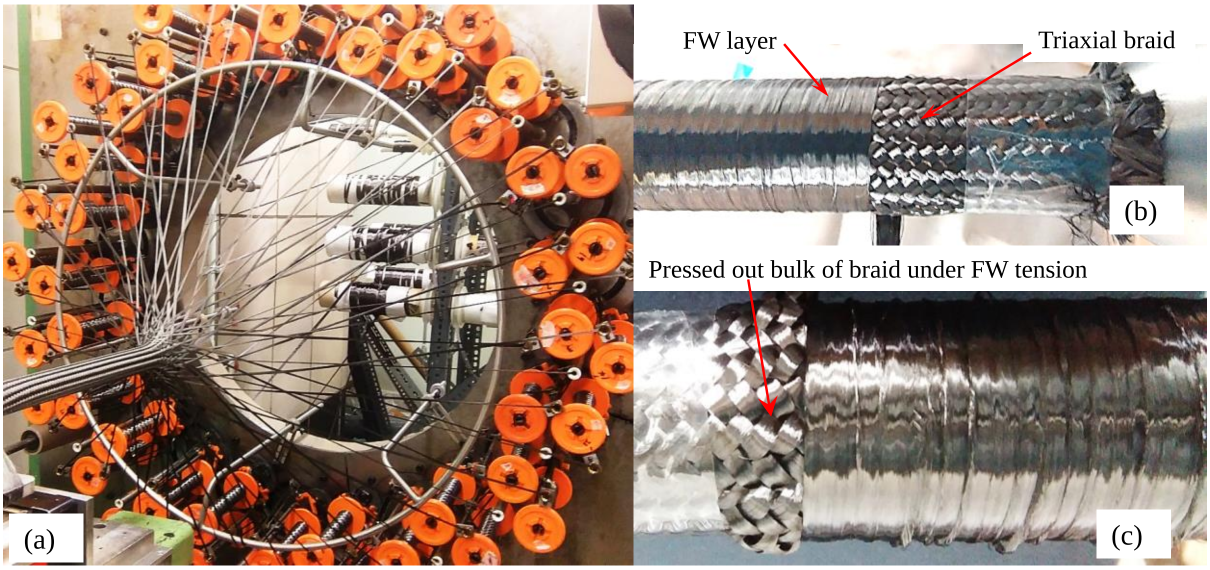

Figure 1(a) Triaxial braiding (±45°/0°) on 25 mm mandrel using a 48 carrier machine (b) Filament winding on the triaxial braid (c) 'Pressed out' braid due to applied pressure on the braid generated by winding tow tension

In this study two comparative layups of triaxial braid and Quadriaxial Quasi-isotropic (QQ) layups were produced to observe difference in structural defect formation. The effect of winding tension on the braided preform can help minimize the formation of wrinkle during *VARI* that is presented later in this article. A triaxially braided $(\pm45°/0°)_4$ layup (TB) was produced to compare the preforming with a QQ structure $(\pm45°/0°/90°/\pm45°/0°)_S$. Both the structures were produced on a 25 mm ID mandrel with 48 tows (800 tex) at ±45° in each layer. The addition of hoop winding reduced the percentage of fibre in other three directions that can be changed based on the desired preform design requirement. The predicted fibre mass in the ±45°, 0° and 90° orientation of the QQ structure was ~62%, ~21% and ~17%. Although the fibre mass was not equal in each direction, the amount complies with the minimum fibre requirement in each direction (12.5%) for a quasi-isotropic layup[4, 5].

WRINKLE FORMATION IN BRAIDED COMPOSITE TUBE:

Formation of wrinkle occurs for both dry fibres 'debulking' process (vacuum bagging) and with prepreg. It is a common defect for manufacturing composite tubes as well as for shell domes where draping of the fabric essentially creates wrinkle. Wrinkle is an imperfection in laminated composite developed by process defects. Laminate wrinkling had been defined as out-of-plane deformation[1] of the layers in a laminate as a result of being 'pressed in'[6]. It is usually observed in the form of unwanted distortion of flat fabric reinforcement while laying on to 'non-trivial' (curved or bent) surface geometry. The geometry of a braided preform on a cylinder is non-trivial. Therefore during the debulking process using vacuum although the layers are allowed to slip, the layer movement due to vacuum consolidation is restricted within the circumference. During this layer slippage, the fibres move outside the edge or the circumference creating wrinkles on the tube wall.

Wrinkle formation is a process defect which can be prevented before curing and once occurred it cannot be eliminated. Wrinkles caused by all the layers in a laminate (severe wrinkle) can have adverse effect when loaded under internal pressure. Whereas wrinkle formed by a few layers (trivial wrinkle) does not affect as much as the former[7, 8]. In addition to the effect under internal pressure, effect of wrinkle was also observed during split disk hoop tensile test[7] while the crack initiation occurred within the resin rich areas of the wrinkle.

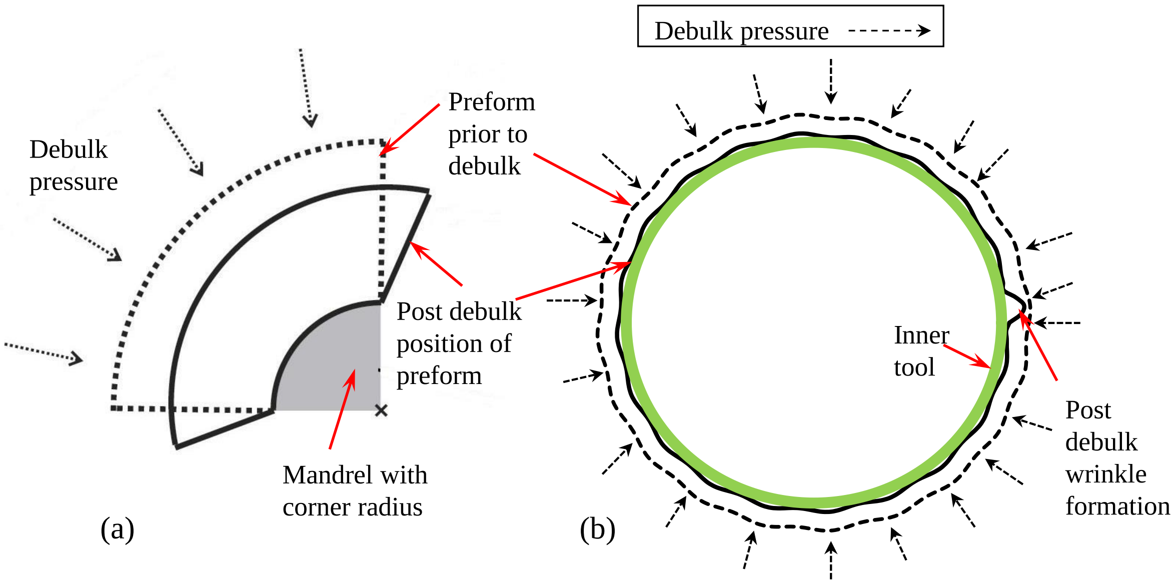

Figure 2: (a) Schematic of 'bookend effect' on a laminate during debulking process due to external pressure over a corner radius where the layers are unconstrained in their position[9] (b) Schematic of wrinkle formation on a cylindrical mandrel during debulking process. Due to external pressure applied around the circumference of the tubular braided preform, the preform buckle to form wrinkle because of the circumference constraint

In a recent investigation, Dodwell et al.[9] have studied wrinkle formation during consolidation of multi-layer carbon fibre laminate on a corner radius (Figure 2a). The authors explained if the layers of fibres on a non-trivial geometry are restricted from slipping over one another during the consolidation process the laminate is prone to instabilities such as wrinkle formation. A schematic of a similar case for a tubular preform on a mandrel is presented in Figure 2b.

A regular (2/2) braided $(\pm 45°)_3$ composite tube was developed on a ~25 mm ID mandrel. A 48 tow (800 tex) braid structure was produced in each layer developing a ~2 mm wall thickness. The composite tube was manufactured using a *VARI* method. As the radius of curvature (1/r) was high along with the high fibre bulk on a smaller circumference, the tube had one wrinkle running along its length (Figure 3a).

Figure 3b and Figure 4 are showing the microscopic images at the circumferential cross section and along the fibre respectively of the braided tube wall with wrinkle. Figure 3 shows the separation of the layers at the wrinkled section of the tube wall from a consolidated state creating resin pockets. In addition all 3 layers of braid appeared to be deformed in the wrinkled section. Hence the wrinkle for this specimen can be considered as ‘severe’. The tube wall thickness in the wrinkled section was more than twice than a regular cross section without wrinkle. The amplitude (Figure 3b) of the wrinkle in this case was about 3.3 mm (~165% of the wall) whereas the wrinkle free wall thickness was ~ 2 mm.

In previous studies[9, 10] the authors proposed that the compressive load during debulking process is a function of radius of curvature. A decrease in radius of curvature will eventually reduce the probability of wrinkling. This observation can be associated with the wrinkles produced on the braided tubes however further investigation on large diameter tube will be required. In addition, decreasing radius of curvature cannot be considered as a probable solution when the radius is constant for certain application of the composite tubes.

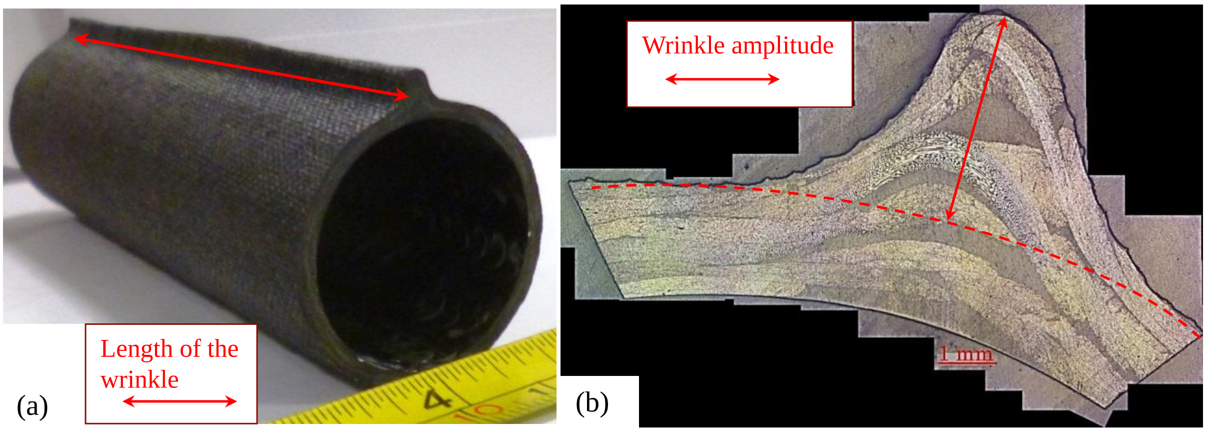

Figure 3: (a) Wrinkle along the length of the 25 mm ID braided composite $(\pm 45°)_3$ *tube (b) Optical microscopic image showing a circumferential cross section of the tube wall with 'severe' wrinkle. The wrinkle amplitude is shown with the arrow where the tube wall thickness is more than twice than it's regular section*

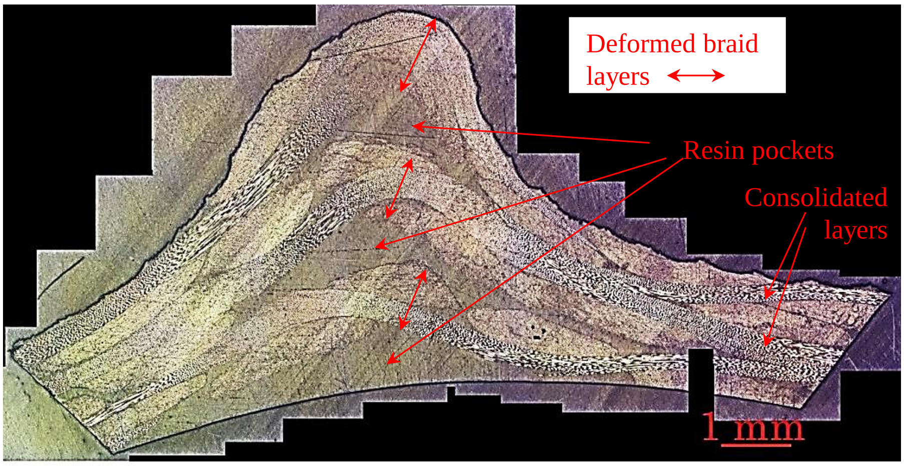

Figure 4: Optical microscopic image of cross section of a 25 mm ID braided tube wall along the direction of bias fibre (45°) with wrinkle

BRAID-WINDING AS A METHOD OF MINIMIZING WRINKLES:

The mechanics of the wrinkle formation can be explained by relaxing stress in the preform layers. Pandey R.K. and Sun C.T. [10] presented how stress relaxation in the layers of laminate occurs. The main reason was identified to be the layer slippage during the resin wetting under vacuum. However while manufacturing the braided tubes, the wrinkle formation was observed during the debulking stage when the braided fibres were still dry. Stress relaxation on the braided preform can be caused by insufficient tow tensioning on the carrier during braiding. Relaxation is also likely to occur after braiding, if separation of the braid sleeve from the machine is carried out without securing the edges. During debulking of a stress-relaxed sleeve, inflatable bladder in the core can be used to apply internal pressure. In this process when the bladder is inflated the pressure is exerted onto the inner circumference of the braid sleeve eventually expanding the braid layer. The expansion of the sleeve occurs up to radial locking position. A consistent pressure from the core will apply stress on to the preform changing the relaxed condition to a compressed consolidated state. In previous investigations, bladder assisted method was used and studied for the purpose of manufacturing the tube using FW [11] and braiding[12] individually. Both of these research focused on consolidation of perform internally along with the benefit of easy extraction by deflating the mandrel. Similar to this study, Bulat et al.[12] used *VARI* method along with bladder moulding for triaxial braided performs. Fibre movement during the consolidation of cylindrical performs was observed during bladder expansion with high pressure. Although the consolidation was increased, yet the expansion was limited only to the bottom layer as was observed from the microscopic images. Consequently the effect on the following layers was insignificant.

Excluding the requirement of bladder moulding, over winding on braid can be advantageous in order to increase the braid consolidation minimising the possibility of wrinkle formation. During the preforming of QQ structure, as the FW was carried out onto the braided preform the winding tow tension consolidated the preform applying enough stress reducing chances of wrinkle formation. As the preform thickness and composite thickness is compared the better consolidation at the preform stage can be observed.

The FW tow tension applies external pressure on the underlying braid and consequently the preform thickness reduces. The FW tow tension (F) and tow width (w) can be used to express the applied pressure [13] as follows.

$$p_0 = \frac{F^{k+1} \sin^2 \alpha}{r_f^{k+1} w^{k+1}} \tag{1}$$

In the above equation p_0 is the pressure applied by k+1 layer. Angle between the fibre and cylinder axis and radius of the added preform layer are indicated by α and r_f respectively.

The applied pressure by the winding tow was preferred to be equivalent of 1 atm (~101 kPa) similar to the envelope pressure during *VARI*. The tow tension during FW was maintained ~6.1 N and ~ 8 N for second and fifth hoop layer. The tension was calculated using equation 1 considering the tow width to be ~5 mm.

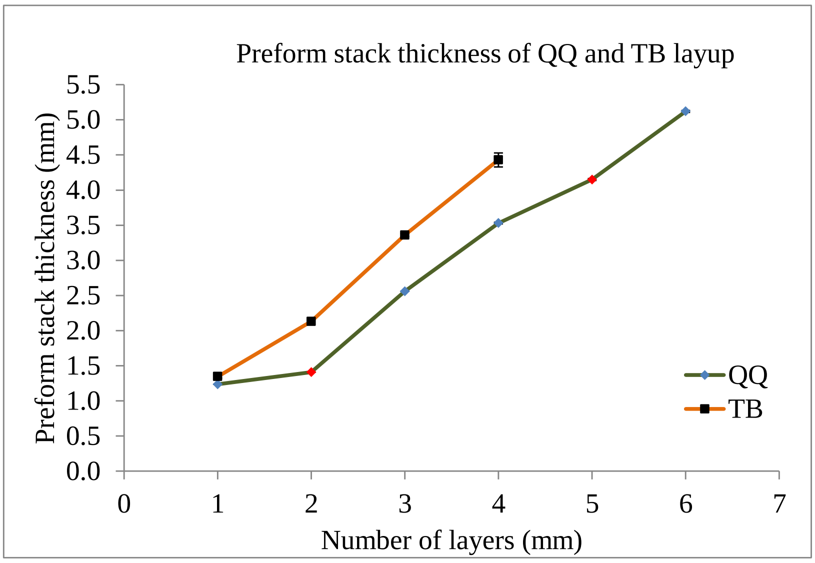

Figure 5: Change in stack thickness due to winding tension in Quadriaxial Quasi-isotropic (QQ) (±45°/0°/90°/±45°/0°)$_s$ layup compared with triaxial (±45°/0°)$_4$ braided (TB) layup

The preform stack thickness build-up between the TB and QQ structure shows the consolidation of the layers during braid-winding in Figure 5. Preform thickness was calculated from the diameter that was measured using vernier callipers. Each FW layer added thickness to the preform. In Figure 5, layer 2 and 5 of the QQ layup indicates the thickness of the stack with FW layers on the braid. The addition of FW layer thickness is observed to be higher for layer 5 (+88°) than that of layer 2 (-84°). Because of the higher winding angle the adjacent tow bands overlapped increasing the thickness of the layer. However the winding tension reduced the bulk thickness of the braid sleeve by pressing out the underlying stress relaxed layer as shown in Figure 1c.

Table 1 Preform and composite wall thickness of the QQ and TB tubes

Tube type	Preform thickness (mm)	Wrinkle free Composite wall thickness (mm)	Composite wall thickness with wrinkle (mm)
Quadriaxial Quasi-isotropic $(\pm45^\circ/0^\circ/90^\circ/\pm45^\circ/0^\circ)_s$	5.12 ± 0.01	4.89 ± 0.13	-
Triaxially Braided $(\pm45^\circ/0^\circ)_4$	4.43 ±0.01	3.83 ± 0.21	6.67 ± 0.33

The QQ and TB composite preforms were resin infused and effect of winding consolidation was observed in the form of wrinkle formation. Figure 6 shows the QQ and TB composites and wrinkle formation was evident on the TB tube. Table 1 shows the preform and composite thickness of the tubes. The TB tube had ~75% increase in wall thickness at the wrinkle peak. Under vacuum the applied envelope pressure on the preform reduced the thickness of the preform. This thickness reduction for QQ structure (~5%) was comparatively less than that in TB structure (~14%). This indicates that the major debulking of the preform for QQ layup occurred during over winding of the braid eventually preventing wrinkle formation.

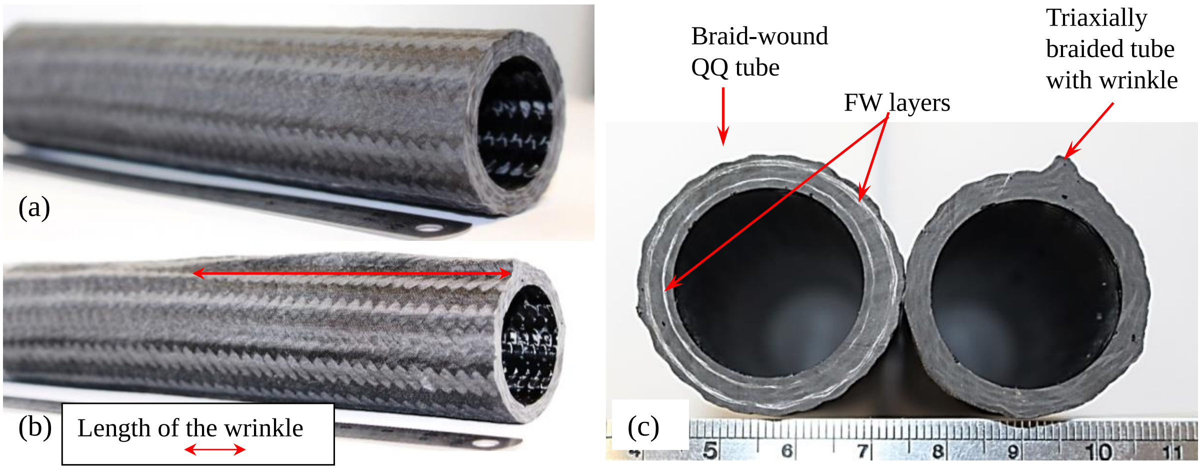

Figure 6 (a) Quadriaxial Quasi-isotropic (QQ) composite tube developed using braid-winding method (b) Triaxially braided (TB) composite tube (c) Cross section view of the QQ and TB tubes; filament wound (FW) layers are shown on the wall of QQ tube

CONCLUSION:

In this study the braid-winding process was used to demonstrate the advantage of the process combination on composite tube manufacturing. Although the study was limited to developing a higher radius of curvature, the effect of curvature aiding the wrinkle formation can be eliminated by over winding on braided layers. Filament winding tension provided consolidation pressure minimizing wrinkles with the additional possibility of achieving higher fibre volume fraction. In addition, braid winding allowed manufacturing of a quadriaxial quasi-isotropic $(\pm45°/0°/90°/\pm45°/0°)_s$ tubular preform. The combined braid-winding process also allows triaxial quasi-isotropic orientation (±30°/90°) offering optimum flexibility in tubular preform design. Different studies on braid-FW layup are being carried out for further investigations on the effect of braid-FW layup on processing.

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