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Effect of heat shrinkable tape layer number on mechanical properties and quality of tubular CFRP components obtained by filament winding

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Abstract. The most common manufacturing process for tubular Carbon Fiber Reinforced Polymer (CFRP) components is Filament Winding (FW), that requires a subsequent curing process to obtain the final parts. The most widely used curing process is the autoclave one, that involves high environmental and economic impacts. Then, other curing solutions must be investigated to find a valuable sustainable alternative. In this context, the present work aims at studying the effect of the number of heat shrinkable tape (HT) layers applied on the wound CFRP components before the oven curing process, on the mechanical properties, thickness uniformity and void content of the tubular parts. To this purpose, ring tensile tests and tomography analysis were performed on ring specimens cut from tubular parts realized by FW, using different HT layers. It was demonstrated that the increase in HT layers allows an improvement both of mechanical properties and thickness uniformity, and a reduction in void content.

Introduction

In recent decades, the manufacturing industry has increasingly focused on developing materials that combine high mechanical performance and light weight in order to optimize energy efficiency and overall system performance [1], [2], [3]. Among these materials, carbon fiber-reinforced polymers (CFRPs) represent a class of composite materials highly valued in advanced technological areas such as the aerospace industry, the automotive sector, and the production of sports equipment [4], [5]. CFRPs feature a structure that achieves an excellent strength-to-weight ratio; they are characterized by high stiffness, tensile strength, light weight and durability, offering reliable and versatile solutions for applications requiring maximum engineering performance [6].

Among the many manufacturing processes, Filament Winding (FW) is one of the most popular technologies for the production of tubular CFRP components, as it enables high precision in fiber placement and good process repeatability [7], [8]. FW involves the controlled winding of resin-impregnated filaments around a rotating mandrel, following specific angles and patterns to optimize the mechanical properties of the final component. This technique is particularly advantageous for the fabrication of cylindrical or spherical structures, such as pressure vessels, drive shafts, and high-performance pipelines [9], [10].

A fundamental aspect of the FW process is the curing of the polymer matrix, which is essential to achieve the desired mechanical properties and reduce internal defects, ensuring the quality of the composite component. There are different methods of polymerization, of which autoclave curing is among the most widely used as it allows uniform pressure to be applied to the entire

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surface of the component, promoting the removal of trapped air and reducing the formation of defects [11], [12]. However, the autoclave process requires significant energy consumption, making the search for alternative solutions sustainable and efficient [13], [14].

In this context, oven curing represents a valid alternative due to its greater operational simplicity and lower costs [15]. Nevertheless, the absence of applied pressure during the curing process can lead to thickness non-uniformity, internal defects, and a reduction in mechanical performance [16]. Additionally, temperature variations, combined with the lack of precise pressure control, can cause defects such as residual voids, micro-cracks, and non-uniformity in resin distribution.

To overcome these challenges, the use of heat shrinkable tape, applied to the components prior to curing, is proving to be promising strategy. HT is a tape designed to be applied around composite components, which contracts when exposed to heat, exerting uniform pressure on the surface of the part. This effect, during the curing phase, can apply consistent pressure to the component, optimizing resin distribution, reducing voids, and improving both mechanical properties and surface quality [17].

The present study aims to analysing the effect of the number of layers of HT applied to tubular CFRP components made by FW. Specifically, it aims to evaluate how the variation of this parameter affects the mechanical properties, thickness uniformity and void content. To this end, ring tensile tests and tomographic analysis were conducted on ring specimens made from tubes cured in an oven with different configurations of HT.

The results of this research will provide a more in-depth understanding of the consolidation dynamics of composite materials in absence of autoclaving and provide practical guidance for improving the quality of the final product through more efficient and environmentally friendly manufacturing techniques.

Materials and Methods

In order to investigate the effect of the HT on the mechanical properties and the void content, a tubular component with a circular section was taken into account, since the pressure during shrinkage is constant for axisymmetric geometry. A filament winding process was used to realize composite tubular components. The composite material was a towpreg characterised by carbon fiber filaments embedded in an epoxy resin matrix. The reinforcement consists of T700 30K carbon fibers with a diameter of 7 μm. The matrix is an epoxy resin (Huntsman International LLC) with a gelation temperature (Tgel) of 90°C and a glass transition temperature (Tg) of 120°C. The towpreg is characterized by a total width and thickness respectively equal to 8mm and 0.2mm, and a weight fraction of CFs and epoxy resin, of 60% and 40%.

The mechanical properties of the composite were calculated from the constituent data sheets using mixture rule [18]. Calculation of the transverse modulus of a unidirectional composite material and of the modulus of an aggregate. Table 1 summarises both the mechanical properties of the constituent materials and composite material.

Table 1: Mechanical properties of CFs, epoxy resin from data sheet, and CFRP calculated by using the mixture rule

	Carbon fiber	**Epoxy resin**	**Composite material**
Elastic modulus (E)	230 GPa	3.5 GPa	75 GPa
Ultimate Tensile Strength (UTS)	4900 MPa	73 MPa	2900 MPa
Density (ρ)	1.8 g/cm^3	1.1 g/cm^3	1.52 g/cm^3

The heat shrink tape used was produced by DIATEX SAS (Saint-Genis-Laval, France). This tape is applied externally to the CFRP tubular component immediately after the filament winding

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process. When heated, the tape shrinks, exerting a compressive force on the underlying material, thereby enhancing its compactness. In particular, the shrinkage begins at 100°C, with a shrinkage of 11% at 150°C, and 15% at 200°C, as reported in the technical datasheet. A key advantage of this tape is its lack of adhesive, which facilitates easy removal after the polymerization process, preventing residues or surface damage.

The filament winding process was performed using the X-Winder machine to manufacture the CFRP tubular components. This automated winding system features four degrees of freedom, each controlled by a dedicated axis. The X-axis translates the cross carriage, controlling its distance from the rotating mandrel. The Z-axis provides linear translation of the carriage along the mandrel's longitudinal axis. The W-axis controls the azimuthal rotation of the mandrel. The U-axis controls the rotation of the fiber deposition head. The coordinated motion of these axes enables the precise winding of the mandrel. The X-axis is crucial for dome formation. The Z and U axes control the fiber placement on the cylinder portion. The W-axis is used to rotate the mandrel. The final fiber angle is a function of both the translational velocity of the deposition head and the rotational speed of the mandrel.

The effect of the layer number of the heat shrinkable tape on both the mechanical properties, void volume fractions, and the void volume was investigated. To this purpose, the composite tubular components were realized by winding three layers of CFRP with a theoretical winding angle of 88°, but different HT layers were used, as summarized in Table 2. The carriage and mandrel maximum speeds were imposed equal to 101.60 mm/s and 3.14 rad/s, respectively.

Table 2: Condition evaluated in this study

Condition	**Composite Layers**	**HT layers**	**n. of specimens**
0 HT Layers	3	0	5
1 HT Layers	3	1	5
2 HT Layers	3	2	5
3 HT Layers	3	3	5

After the winding process, the tubular components were removed from the winding machine and placed in a FALC muffle furnace. This furnace allows a maximum temperature of 1200°C, for the curing process, to be reached. According to the physical properties of the epoxy resin, the thermal curing process consists of two distinct stages. The primary cure is conducted at 120°C for a duration of 2 hours. To ensure complete polymerization and optimal material properties, a secondary post-cure stage is required. This involves maintaining the chamber temperature at 150°C for an additional 2 hours. The part is then allowed to cool to room temperature via natural convection (air cooling).

Then, ring specimens were obtained from the CFRP tubular components by means of drilling and cutting operation, according to ASTM D2290 standard (Procedure A). The split-disk test is a standard method for characterizing the circumferential tensile behaviour of filament-wound composites. The mechanical properties of the ring tensile specimens were evaluated by means of the split-disk test carried out on a servo-hydraulic testing machine (MTS 810®) equipped with a 250 kN load cell. During tests, the crosshead speed was kept constant at 0.1 mm/s. The experimental results were plotted as applied load versus displacement curves from which the hoop tensile strength was evaluated by using Equation 1:

$$\sigma_{HTS} = \frac{P}{2 \cdot A_{min}} \quad (1)$$

in which P [kN] is the maximum load during the tensile test and A_{min} [mm^2] is the minimum area between the two reduced sections.

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Finally, the X-ray Computed Tomography (X-CT) scan was performed using a Zeiss METROTOM 1500 CT to evaluate the void volume fraction (VVF) and Void Volume (VV). The system was equipped with an X-ray tube with a minimum focal spot of 7 μm, a maximum accelerating voltage of 199 kV and a maximum current leakage of 1000 μA. The source-detector distance was maintained at 1500 mm with a maximum measuring range of 350 mm x 300 mm and a detector resolution of 2048 x 2048 pixels. The voxel size of the X-CT is 50.7 μm. The scanning was carried out after the machining necessary to produce the ring specimen. In particular, the void analyses were performed on the central ring of the tubular component, as this is the area where the machine works at full capacity, so the ring quality should be higher with respect to the other zone.

The tubular components produced both with and without the HT are shown in Figure 1.

(a) Without HT (b) With HT



Figure 1: Tubular parts and ring specimens obtained (a) without and (b) with HT.

Results and Discussion

In order to evaluate the effect of the heat-shrinkable tape application on the mechanical properties of CFRP wound parts, ring specimens, obtained from tubular components, were tested using ring tensile tests. Figure 1 shows the typical hoop tensile stress versus displacement curves of CFRP ring specimens subjected to the split ring tests. Irrespective of the number of HT layers, it can be observed that the HTS rises with increasing displacement up to a peak value corresponding to the ring fracture. The HT tape application involves an increase in the hoop tensile strength as compared to the condition without the HT tape. Furthermore, it can be observed that the HTS values increase as the number of HT tape layers applied increases, even though such effect tends to decrease with increasing the HT layers. As a matter of fact, the application of a HT layer (condition 1 HT Layer of Table 3) leads to the obtaining of an increase in HTS value of about 38.7% as compared to the condition without the tape; as the number of HT layers increases, the HTS increases by 53.4% (condition 1 HT layer) and 64.9% (condition 2 HT layers), respectively, compared to the condition 0 HT layer. The hoop tensile strength values obtained at different HT layers are summarized in Table 3. Since the weights of the specimens are different between the different analyzed conditions, the specific HTS was evaluated (Table 3).

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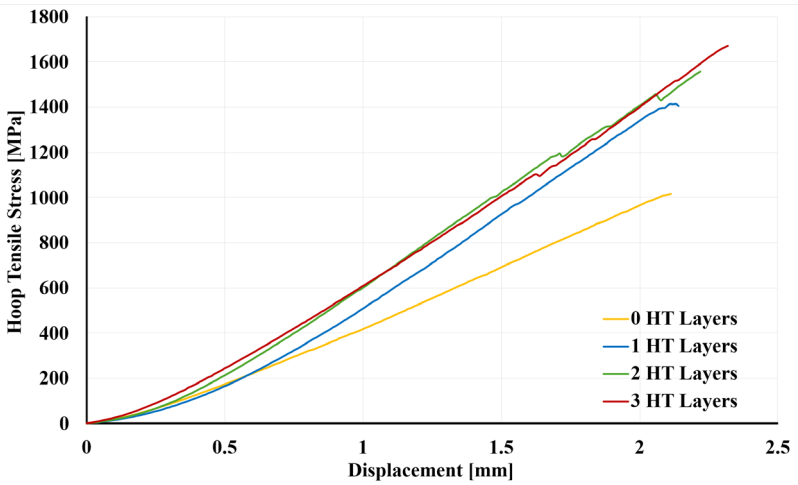


Figure 2: Effect of the number of HT layers on the typical hoop tensile stress - displacement curves obtained from CFRP ring specimens

Table 3: Average HTS, thickness, weight, specific HTS and the respectively percentual standard deviation obtained

	HTS [MPa]	Thickness [mm]	Weight [g]	Specific HTS [MPa/g]	Load [kN]
0 HT Layer	1014.77 ± 4.1%	1.49 ± 7.7%	12.79 ± 3.8%	79.33 ± 5.9%	52.92 ± 3.9%
1 HT Layer	1407.36 ± 2.3%	1.33 ± 3.6%	11.16 ± 2.9%	126.11 ± 2.95%	61.11 ± 2.4%
2 HT Layers	1556.39 ± 2.2 %	1.32 ± 3.3%	10.74 ± 2.4%	144.92 ± 2.8%	65.55 ± 1.9%
3 HT Layers	1672.95 ± 1.9%	1.20 ± 3.4%	10.40 ± 2.7%	160.86 ±2.7%	66.65 ± 2.1%

The improvement in mechanical properties of the CFRP ring specimens given by the application of HT layers can be also observed by the Figure 2 in which the specific HTS values as a function of the number of HT layers is shown. The specific HTS increases as the number of HT layers increases, with a non-linear trend. To evaluate the benefit related to the application of HT tape, a linear trend between two consequent conditions (i.e. 0 - 1 HT Layers; 1 - 2 HT Layers; 2 - 3 HT Layers) was considered. In particular, the ratios $\frac{\Delta y}{\Delta x}$ reported in the figure correspond to the slopes of the different segments of the curve, representing the rate of increase of specific HTS for each additional layer. Specifically, the slope of the linear trend represents the increment of the specific HTS between the conditions considered. The application of heat-shrink tape improves the specific HTS, but with a decreasing marginal benefit as the number of layers increases. The addition of a layer has the greatest impact on HTS ($\frac{\Delta y}{\Delta x} = 46.77$), suggesting that the application of pressure during curing significantly reduces structural defects (such as voids or poor resin impregnation). Applying two layers instead of one, a reduced improvement can be obtained ($\frac{\Delta y}{\Delta x} = 18.81$), indicating that beyond a certain level of compression, the benefit stabilizes. This can be also highlighted with the addition of three HT layers ($\frac{\Delta y}{\Delta x} = 15.94$).

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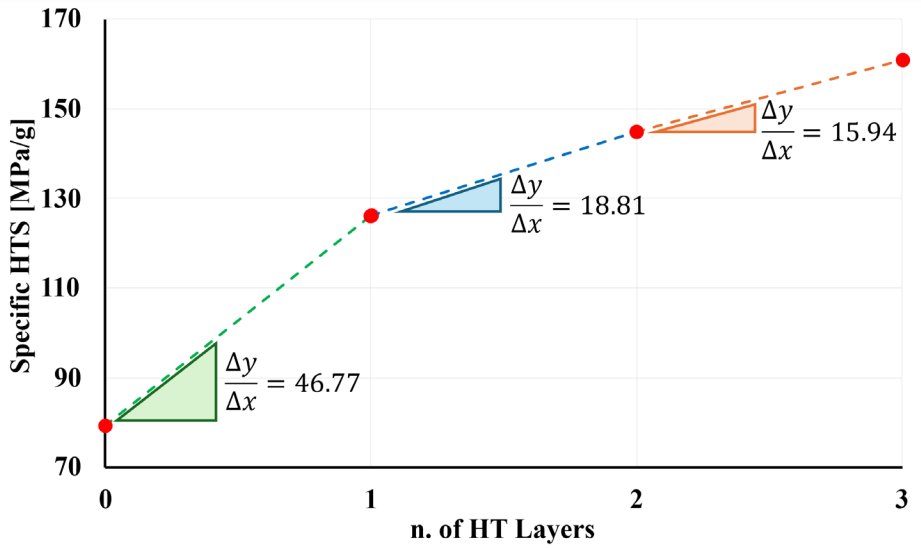


Figure 3: Influence of the number of HT tape layers on the specific HTS

The increase in the hoop tensile strength with HT layers can be attributed to the reduction in the ring thickness, due to the compressive force applied to the tape on the tubular component during the curing phase. Furthermore, the reduction in thickness leads to a decrease in the void content in the tubular component. To this purpose, Figure 3 shows the results obtained from the X-CT for each condition investigated, in order to quantify the Volume Void Fraction, and to highlight the void distribution in ring specimens. The analysis of void distribution in the ring specimens reveals a clear alignment of voids along the direction of fiber deposition. This pattern suggests a strong correlation between the manufacturing process and void formation, indicating that voids are inherently linked to the material deposition technique. The specimen characterized by the highest void content is the one manufactured without heat-shrink tape (0 HT layer). As a matter of fact, it exhibits larger and more irregularly distributed voids, with a void volume fraction of about 3.1%. When HT tape is applied (1 HT layer), the void fraction decreases significantly, resulting in smaller and more evenly distributed voids. However, beyond the first layer of HT tape, the reduction in voids becomes marginal, suggesting that additional layers do not substantially enhance the compaction. In fact, the void volume fractions are about 0.61%, 0.58%, and 0.53% for the condition with 1, 2, or 3 HT layers, respectively. The observed reduction in thickness is directly related to the decrease in void content. The external pressure exerted by the HT tape during the curing process enhances material compaction, leading to a more structurally sound component with few internal voids. This improvement in compaction results in better mechanical properties and overall material quality.

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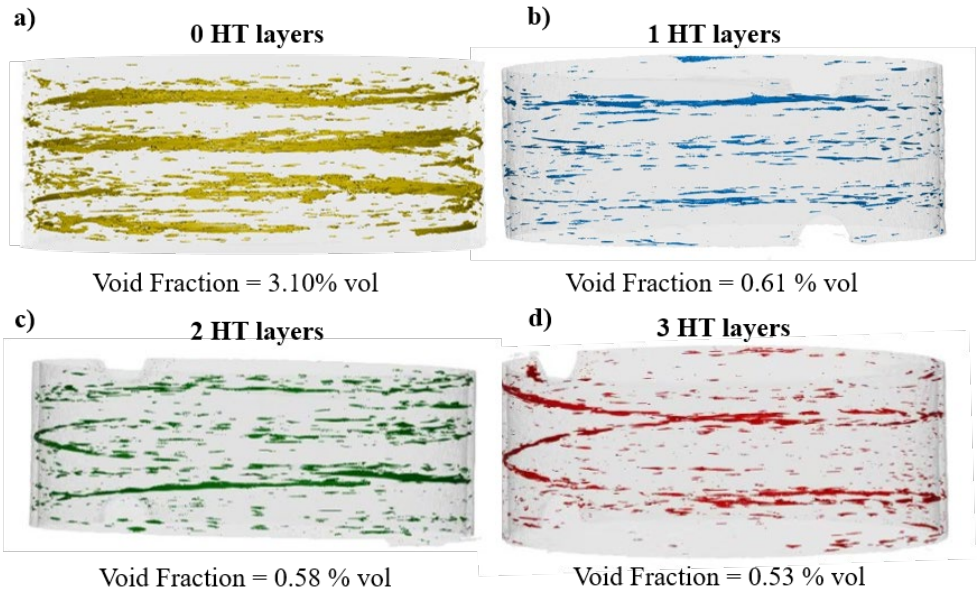


Figure 4: Effect of the number of HT layers on the void fraction: (a) without HT, (b) 1 HT layer, (c) 2 HT layers, and (d) 3 HT layers.

In Figure 4 the void volume dimensions are shown, as a function of the number of HT layers applied. The sample without HT tape (0 HT layer) is characterized by the highest void volume (i.e. 230.23 mm³). The widespread presence of large voids (red areas) indicates a lack of external pressure during polymerization, which prevented the escape of trapped air and led to the formation of macroscopic defects. The application of a single layer of HT tape (1 HT layer) significantly reduces the total void volume to 43.52 mm³, with a predominance of small voids (green/yellow areas). This result demonstrates that the compression exerted by the tape facilitates the elimination of trapped air, significantly improving the compaction of the composite materials. By applying two layers of HT tape (condition 2 HT layers), the total void volume is slightly reduced to 43.27 mm³. However, the change compared to the sample with only one layer is minimal, suggesting that the effect of compression reaches a limit beyond which further increments do not provide significant benefits. The application of the third layer (3 HT layers) leads to a marginal reduction in the total void volume, which stands at 37.39 mm³. The difference compared to previous samples is negligible, confirming that the effectiveness of the compression gradually decreases with increasing layers. The reduction in total void volume has a direct impact on the structural quality of the composite material, as the presence of internal defects compromises mechanical properties. The application of the first layer of HT tape is the most effective in reducing internal porosity, with a decrease in the total void volume of approximately 81% compared to the sample without HT tape. From the first to the second layer, and from the second to the third layer, a reduction of 0.25% VVF and 0.12% VVF, respectively, can be obtained. These results indicate that the effect of the compression exerted by the heat shrink tape reaches a plateau beyond which further increments are no longer effective. Residual voids are mainly concentrated along the fiber direction of the composite material, suggesting that the initial deposition process significantly influences the formation of porosity and must be optimized to obtain structurally superior components. The smaller voids in volume, on the other hand, are related to the impregnation phase for each condition.

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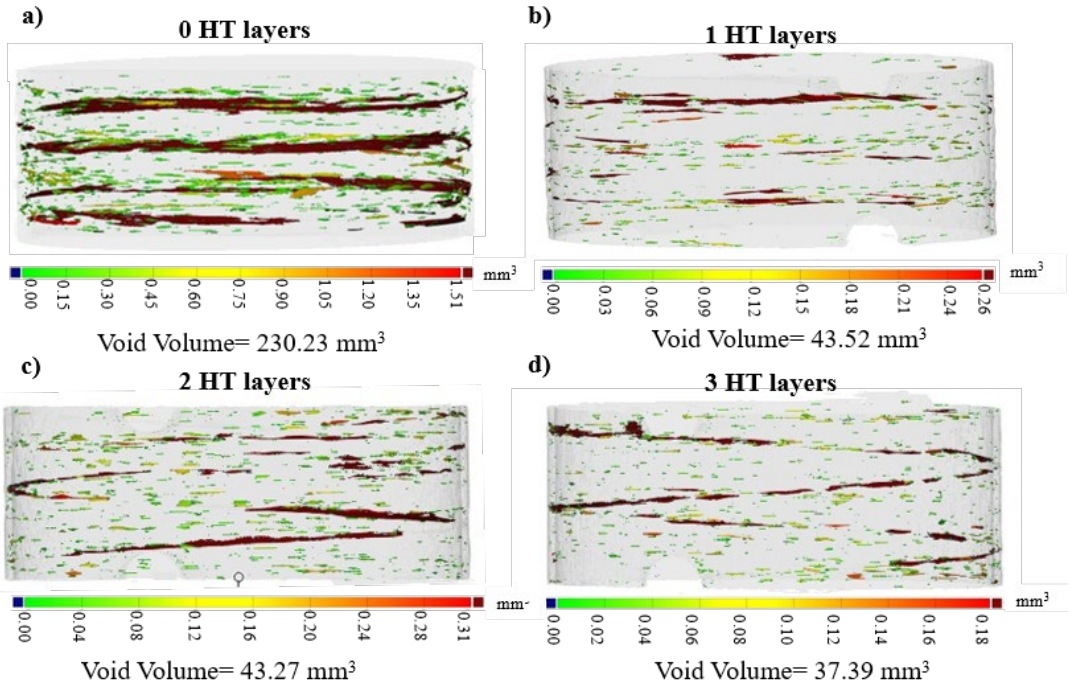


Figure 5: Effect of the number of HT layers on the void volume: (a) without HT, (b) 1 HT layer, (c) 2 HT layers, and (d) 3 HT layers.

Conclusions

The present study investigated the effect of the heat-shrinkable tape application and of the number of HT layers on the mechanical properties, void content, and structural quality of carbon fiber-reinforced polymer tubular components manufactured via filament winding and cured in an oven. The main outcomes can be summarized as follows:

- The HTS and specific HTS increase with increasing the number of HT layers applied before curing phase. Specifically, the HTS improves of about 47 MPa by applying 1 HT layer of about 19 MPa by adding a second HT layer, and of about 16 MPa by applying the third HT layer.
- The HTS and specific HTS tend to decrease with increasing the number of HT layers, with a nonlinear trend in which the first layer provides the highest improvement (equal to 46.77 MPa).
- The increase in the hoop tensile strength with HT layers can be attributed to the reduction in the ring thickness, due to the compressive force applied to the HT on the tubular component during the curing phase.
- The improvement in compaction results in better mechanical properties and overall material quality.
- The voids are typically aligned along the direction of fiber deposition, indicating a strong correlation between manufacturing processes and void formation.
- The application of the HT tape leads to a decrease in the void volume fraction from 3.1%, in the condition without HT, to 0.53% in the condition with 3 HT layers.
- Additional layers of HT result in marginal reductions both in mechanical properties and void fraction, this indicates that the effectiveness of HT tape compression reaches a plateau beyond one layer.

Further studies are recommended to explore the effect of HT tape in tubular component with a greater thickness with respect to the tubular components investigated in this study, the effect of

the use of the breather and peel ply, and the use of expandable mandrels in these curing processes with HT tape.

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