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Editorial

This collection contains the proceedings of the 21st European Conference on Composite Materials (ECCM21), held in Nantes, France, July 2-5, 2024. ECCM21 is the 21st in a series of conferences organized every two years by the members of the European Society of Composite Materials (ESCM). As some of the papers in this collection show, this conference reaches far beyond the borders of Europe.

The ECCM21 conference was organized by the Nantes Université and the Ecole Centrale de Nantes, with the support of the Research Institute in Civil and Mechanical Engineering (GeM).

Each volume gathers contributions on specific topics:

- **Vol 1. Industrial applications**
- **Vol 2. Material science**
- **Vol 3. Material and Structural Behavior – Simulation & Testing**
- **Vol 4. Experimental techniques**
- **Vol 5. Manufacturing**
- **Vol 6. Multifunctional and smart composites**
- **Vol 7. Life cycle performance**
- **Vol 8. Special Sessions**

Nantes, the birthplace of the novelist Jules Verne, is at the heart of this edition, as are the imagination and vision that accompany the development of composite materials. They are embodied in the work of numerous participants from the academic world, but also of the many industrialists who are making a major contribution to the development of composite materials. Industry is well represented, reflecting the strong presence of composites in many application areas.

With a total of 1,064 oral and poster presentations and over 1,300 participants, the 4-day event enabled fruitful exchanges on all aspects of composites. The topics that traditionally attracted the most contributions were fracture and damage, multiscale modeling, durability, aging, process modeling and simulation and additive manufacturing.

However, the issues of energy and environmental transition, and more generally the sustainability of composite solutions, logically appear in this issue as important contextual elements guiding the work being carried out. This includes bio-sourced composites, material recycling and reuse of parts, the environmental impact of solutions, etc.

We appreciated the high level of research presented at the conference and the quality of the submissions, some of which are included in this collection. We hope that all those interested in the progress of European composites research in 2024 will find in this publication sources of inspiration and answers to their questions.

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Integrating Fiber Overbraids in Composites for Enhanced Compressive Performance

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Abstract

Advanced composite materials have become the key to many modern engineering applications due to their material property flexibility and high strength-to-weight ratio. However, achieving optimal compressive performance is still challenging, especially for systems where the ability to maintain the material's structural integrity under compressive loads is highly important. Overbraids represent a unique form of reinforcement, as they provide additional support and resistance to compressive forces. This paper discusses the process and challenges of overbraiding small-diameter pultruded rods (0.8 mm), with overbraids integration in strut manufacturing from design consideration to manufacturing using a resin transfer moulding (RTM) technique and optimization strategies. A novel and rigorous approach to the attainment of a consistent internal geometry of triaxial overbraids within a composite strut is presented. The micro-CT characterization of composite struts having three different lay lengths (2.5, 4, 6 mm) and braid angles (34, 49, 61^0) are also presented. The result shows the level of resin infusion with shear support on the surrounding matrix region of the overbraids within the struts. The results from the micro-CT scans show that overbraided rods were fully wetted with epoxy resin with no recorded visible void.

1. Introduction

The exceptional blend of high-strength and low-weight characteristics found in carbon fibres and their composites makes them perfect for a wide range of present and emerging weight-sensitive applications, including wind energy, sports and leisure, aerospace, defence and the automotive industry [1, 2]. Advanced composite manufacturing processes are quite complex [3-5] and these processes generally consist of a forming phase of dry preform (textile reinforcement) commonly applied in composite manufacturing processes like the resin transfer moulding (RTM) technique [6]. RTM method in composite manufacturing processes is associated with several defects which include fibre bridging, void formation, resin-rich areas, resin starvation, fibre misalignment and surface imperfections[7, 8]. To address these flaws in composite manufacturing, thorough process optimization is essential.

Over-braiding which is a lean manufacturing method that is highly automated with minimal waste has gained considerable attention from the aerospace industries for structural element manufacturing over the last four decades [9, 10]. This technology fabricates fibre overbraids directly into complex preforms with no intermediate production process. This is mostly because of the preform's three-dimensional fibre arrangement, which promotes improved load distribution and stronger resistance to crack propagation and delamination [11-13]. Triaxial structures can offer improved in-plane strength, stiffness and toughness, which makes these composites useful for high-performance mechanical applications.

This study aims to explore the impact of fibre overbraids, overbraid parameters (lay lengths, braid angles and overbraid geometries) within a composite strut for advanced composite materials under compressive loading. In the meantime, 3D triaxial overbraided composite struts were manufactured. Studies on the overbraid alignment and level of resin infusion on the overbraids within the struts architecture were done using a micro-CT scan. Scientific insight into the strut manufacturing process using overbraids and controlled positioning of the overbraids within the cross-section of the strut is presented. The study further attempts to contribute to the development of innovative composite materials with higher structural integrity and durability for a variety of engineering applications. Scientific insight into the strut manufacturing process using overbraids and controlled parameters within the cross-section of the strut is also presented.

2. Materials and Methods

2.1. Materials

In this study, carbon fibre-epoxy pultruded rods of 0.8 mm diameter supplied by Easy Composite were used as a core to overbraid Toray carbon fibre T300. According to the manufacturer's datasheet, the Toray carbon fibre T300 has a tensile modulus of 230 GPa and 1.5 % strain at failure [14]. M135 epoxy resin and MH137 hardener supplied by Gurit UK were used for the manufacturing of the overbraided struts. The cured epoxy resin has an elastic modulus of 3.3 GPa and a density of 1.1 g/cm^3 according to the manufacturer's datasheet.

2.2. Sample Preparation

2.2.1 Overbraid fabrication

1K tows of Toray T300 Caborn fibres [14] were used to manufacture the overbraids. The overbraiding was performed on a 16-carrier Herzog 1/16/80 circular maypole microbraider (Fig. 1). However, the overbraids were manufactured with a mandrel (pultruded rods of 0.8 mm diameter as a core) on a half-capacity (8 tows), four rotating clockwise and four rotating anti-clockwise for ease of strut manufacturing. Carrier take-up/rotation speed of 75 rpm was used for the overbraiding. The fabricated overbriads have a pitch length of 500 mm and diameter of 1.2, 1.12 and 1.08 respectively for the 2.5, 4 and 6 mm lay lengths investigated. The fabricated overbriads at the three different lay lengths (2.5, 4 and 6 mm) studied have corresponding braid angles of 34, 49 and 61^0. As seen in Fig. 2a, overbraid lay length is the length of the braid's axis along which a whole cycle of intertwining takes place. In simpler terms, it is the length of the braid needed for a single strand to make a full rotation around the braid's axis. In general, a tighter braid is produced by a shorter lay length with lower braid angles while loose braids are produced by a longer lay length with higher braid angles. The nominal braid angle was calculated using Eq. (1). Figure 2(b) shows the geometric parameters in overbraiding.

$$a_{nominal} = tan^{-1}\left(\frac{l_l}{\pi D}\right) \quad (1)$$

Where ɑ = braid angle, l_l = lay length, π = 3.14 and D_b = overbraid diameter

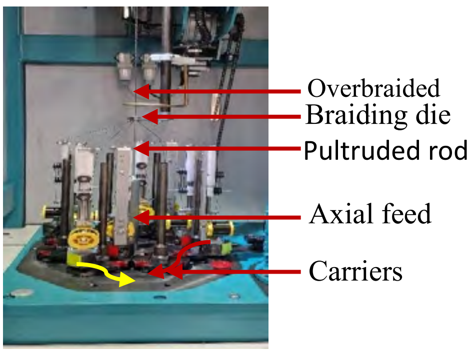

Fig 1. Herzog 1/16/80 circular maypole micro braider showing 8 carriers of Toray T300 carbon fibre

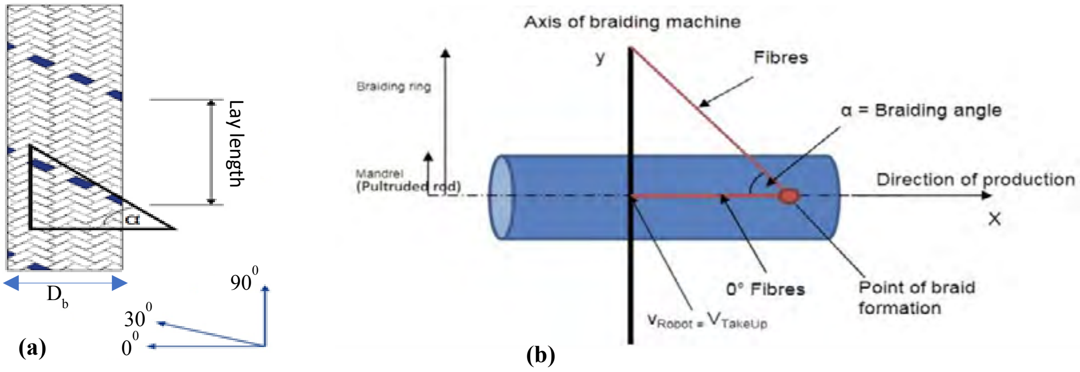

Fig 2. Schematic representation of (a) overbraid lay length and angles (b) geometric parameters in braiding adapted from [15].

2.2.2. Strut Manufacturing

The overbraided rods at different lay lengths and braid angles were used to manufacture composite struts of 500 mm long and 6 mm diameter using flexible tooling according to the manufacturing set-up as shown in Fig. 3. The single overbraids (12 overbraids for each lay length) were first loaded into the flexible tool (Fig. 3). This was done carefully to avoid fibre/core breakages within the tool. The composite struts were manufactured by mixing the resin and hardener according to the manufacturer's recommendation, followed by degassing in a vacuum for 30 min to remove air bubbles. The resin was infused into the flexible tool guided by a copper pipe to maintain a circular cross-section. A resin transfer moulding (RTM) technique with compressed air using an initial pressure of 0.5 x 10^5 Pa with a gradual increase to a maximum of $3x10^5$ Pa was used for the manufacturing. The strut samples were cured in a temperature-controlled oven with a thermocouple at 80^0 for 10 hr.

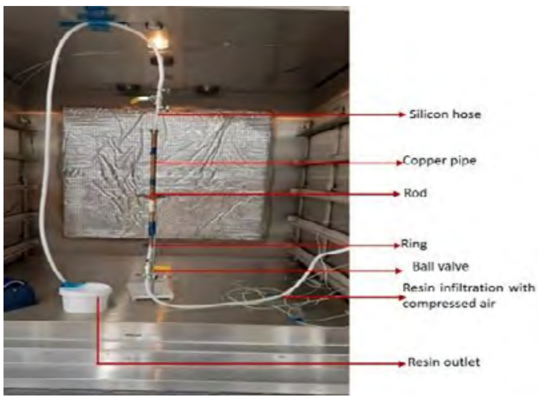

Figure 3. Manufacturing set-up for the over-braided composite struts with RTM

2.3. X-ray Micro-Computed Tomography (Micro-CT)

Sections of the cured strut samples were examined using X-ray computed tomography (XCT) as shown in Fig. 4. The sample imaging was performed with a Nikon XTH-320 with a reflection head and flat panel detector. A 90 kV beam energy, 77 µA beam current, 6.9 W power and 2000 projections for every scan with 4 frames for each projection were utilized to perform the scan. An effective pixel size of 7 µm was used for every sample diameter. Nikon Metrology's CT Pro 3D 6.8.7977.22560 software was used to reconstruct the scanned samples. Volume graphics (VG) Studio Max version 2.4 post-processing tool was used to analyze the scanned images for voids, overbraid distribution and internal arrangements of the overbraids within the struts. The image threshold was set at the beginning of image processing to extract the region of interest from the whole volume.

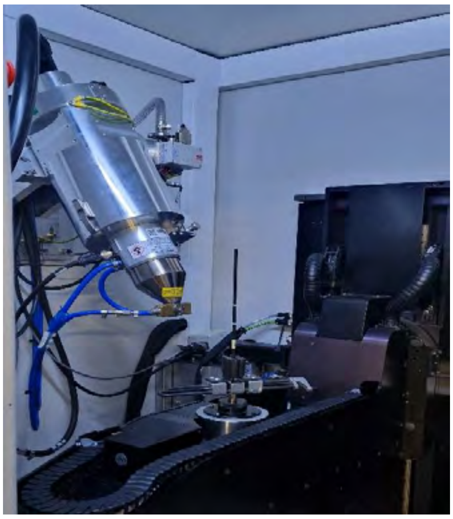

Fig. 4. Test setup for the Micro-CT

3. Results

3.1. Overbriad fabrication

Figure 5 shows the fabricated overbraid samples at different lay lengths and braid angles (5a-c). The minimum lay length achieved with the T300 carbon fibres at the time of fabrication was 2,5 mm. Beyond this length, the fibres break and drop down on the carrier. With the minimum lay length of 2.5 mm, the overbraids become tighter on the rod geometry and produce fuzzy carbon which is expected to provide better support between the rods for improved compressive performance.

The 0.8 mm diameter rod overbraided with Toray T300 carbon fibre with 8 tows at three different lay lengths of 2.5, 4 and 6 mm produced ovebraid samples with a cross-section of 1.20, 1.12 and 1.08 diameters respectively. A 50, 32, and 28 % diameter increment respectively for the three laylengths (2.5, 4 and 6 mm) investigated.

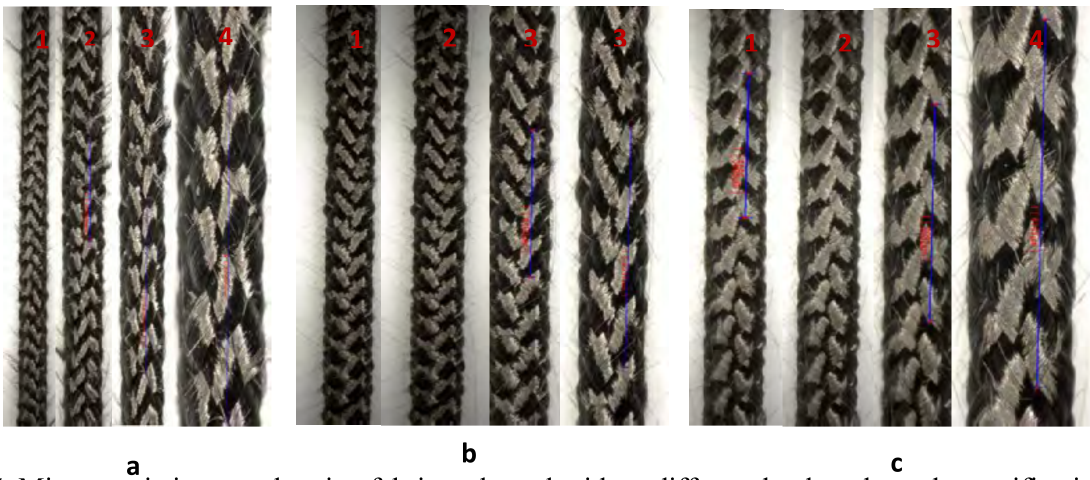

Fig. 5. Microscopic images showing fabricated overbraids at different lay lengths and magnifications for (a) 2.5 mm lay length (b) 4 mm lay length (c) 6 mm lay length at x20, x25, x30 and x40 magnifications

3.2. Micro-CT

The result of the CT scan of the overbraided struts is shown in Figs. 6-8 for the top, front, right and 3D images (a-d). It was observed from these Figures that the overbraids were wetted with epoxy resin but not uniformly distributed (Fig. 6 and 8) loosely fitted with an un-even distribution (Fig. 7) within the strut cross-section creating some more resin-rich areas. A few small voids were detected within the longitudinal sections of the pultruded rods. A slight misalignment was noticed from the right and front views of the images (Figs. 6-8).

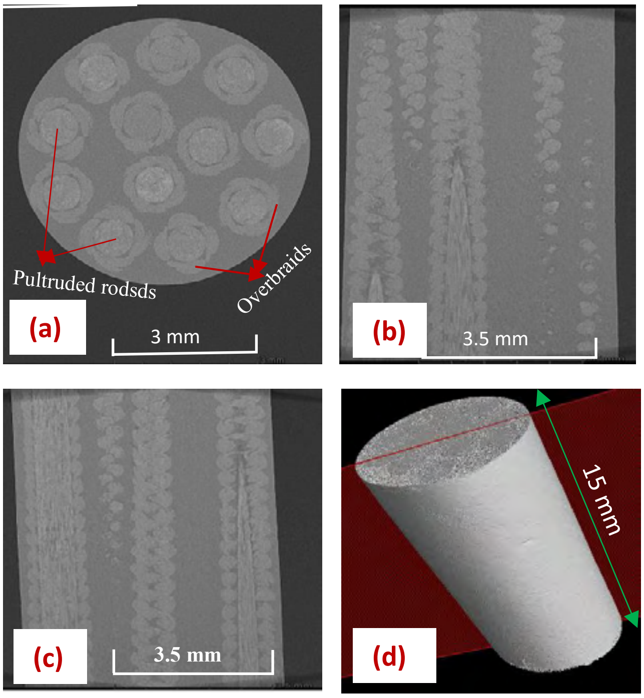

Fig. 6. Micro CT composite strut (manufactured @3 x 10^5 Pa) at 2.5 mm lay length and 34^0 braid angle showing (a) Top, (b) Front (c) Right and (d) 3D.

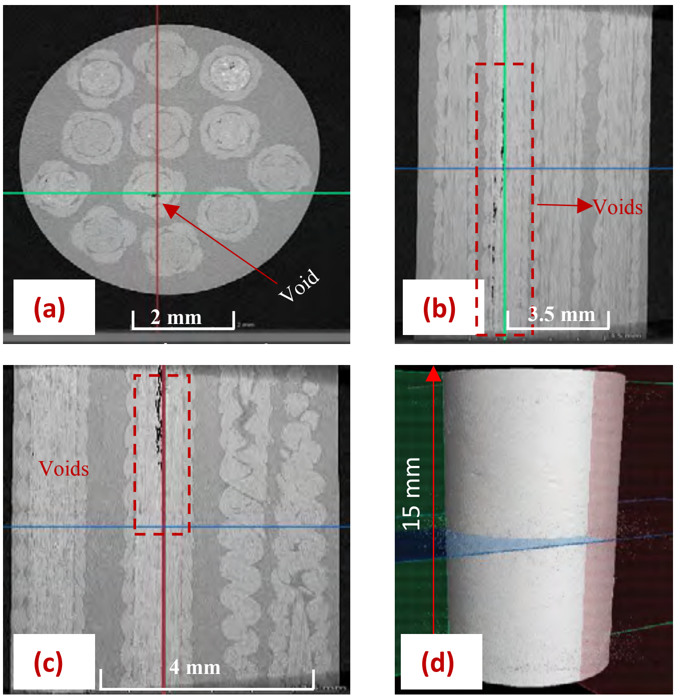

Fig. 7. Micro CT composite strut (manufactured @3 x 10^5 Pa) at 4 mm lay length and 49^0 braid angle showing (a) Top, (b) Front (c) Right and (d) 3D.

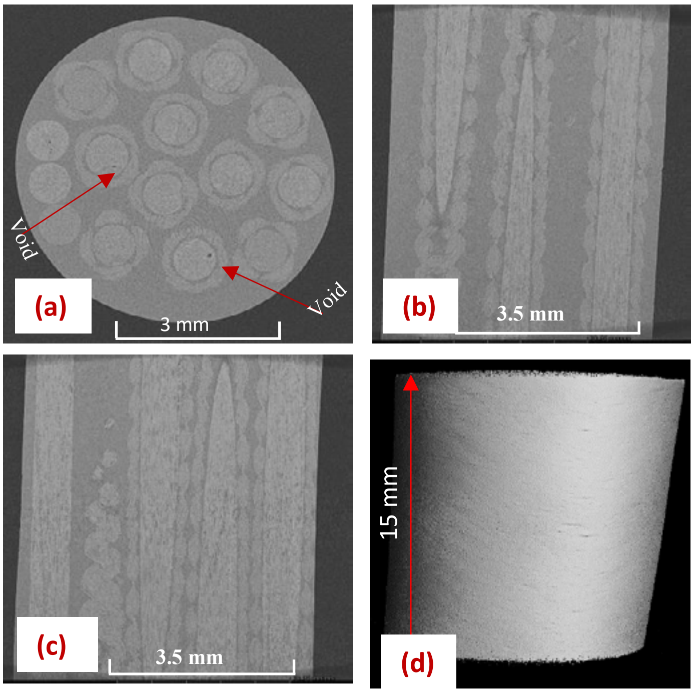

Fig. 8. Micro CT composite strut (manufactured @3 x 10^5 Pa) at 6 mm lay length and 61^0 braid angle showing (a) Top, (b) Front (c) Right and (d) 3D.

4. Discussion and Next Steps

The present study confirms that overbraid lay length and angles strongly affect fibre interaction during overbraid manufacturing. These effects were seen within the overbraid architectures with the smallest lay length (2.5 mm) producing fuzzy carbon (Fig. 5(a) which is thought may give shear support in the matrix region between the rods in hierarchical composite architectures [12]. Increased share support may achieve improved compressive performance in composite struts. However, the highest lay length (6 mm) investigated exhibited smoother surface architecture as seen in Fig. 5(c) with a higher braid angle (61^0). The 4 mm lay length (Fig. 5(b) was at the intermediate with partly fuzzy carbon and a braid angle of 49^0 higher than 2.5 mm lay length.

It was observed from the study that the initial rod (mandrel) position is a very significant parameter that requires attention when operating the overbraid process as it can affect the braid angle if not well positioned. There may be instabilities in the braid angles at the start of the rod due to the initial random dispersion of the fibres around the circle of the rod tip [17-20]. From this study, it was observed that the fibre interaction plays a vital role in determining the fibre distribution when the process transitions from an unstable state to a steady one. Such circumstances include a quick shift in the axis position, the rod cross-section, the spool angular velocity, the take-up speed or in the event of a reversal. The coefficient of friction of the overbraids also affects the process and it may be necessary to devise an experimental technique to measure it. The approach might be expanded with the potential to create different configurations including multiple lay-up overbraiding, triaxial overbraiding with an additional axial yarn group or different fibres.

The manufactured overbraided strut samples were examined using micro-CT as shown in Figs. 6-8 for (a) Top, (b) Front (c) Right and (d) 3D respectively. The minimum intensity projection approach was utilized to obtain the projection image. As shown in Figures 6 and 7, the cross-section of the strut

contains 12 overbraids for the 2.5 and 4 mm lay lengths respectively while the 6 mm lay length (Fig. 8) contains 12 overbraids and 3 single pultruded rods proving the possibility of achieving different overbraid/rod geometries within the cross section of a composite strut. There was evidence of visible voids within the pultruded rods bearing the overbraids. These identified voids were also visible in the high-intensity region and arose from either the rods' manufacturing process or material quality. This study has proved that the targeted overbraid geometries and internal architectural alignment of the overbraids/pultruded rods within the cross-section of the strut can be achieved. It is also possible from Fig. 8 that combining different geometries (overbraids and smaller single pultruded rods) can be achieved for increased fibre volume fraction. The overbraids were not uniformly distributed within the struts as a result of the tooling used for the manufacturing. Apart from the voids observed within the pultruded rods, the resin generally wetted the overbraids and no other was observed within the strut.
We plan to manufacture and test composite struts made from metal tooling with different geometries for hierarchical structures. As part of an ongoing investigation, multi-material overbraids that combine the advantages of carbon and aramid fibres will also be investigated. Hierarchical structures are truly obtained when overbraids with pultruded rods are integrated into a composite system. With inspiration from natural composites, advanced overbraids and resins will be developed for strut manufacture as part of NextCOMP structural deliverables at several length scales.

5. Conclusion

Overbraiding of 0.8 mm diameter pultruded rods at three different lay lengths of 2.5, 4. 6 mm and various braid angles (34, 49, 61^0) have been investigated using carbon fibre for strut manufacturing. The carbon fibre overbraids at the lowest lay length (2.5 mm) produced fuzzy carbon which is expected to support the resin during bonding and improve the compressive performance. The higher lay lengths (4,6 mm) on the order hand produced smother overbraid surfaces with maximum braid angles of 49 and 61^0 respectively, making manufacturing easier with improved resin infusion of the overbraided rods.
The manufactured struts have demonstrated that the overbraids can be successfully wetted during RTM manufacturing but may require a higher pressure with a metal mould to achieve composite struts with circular cross-sections.

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