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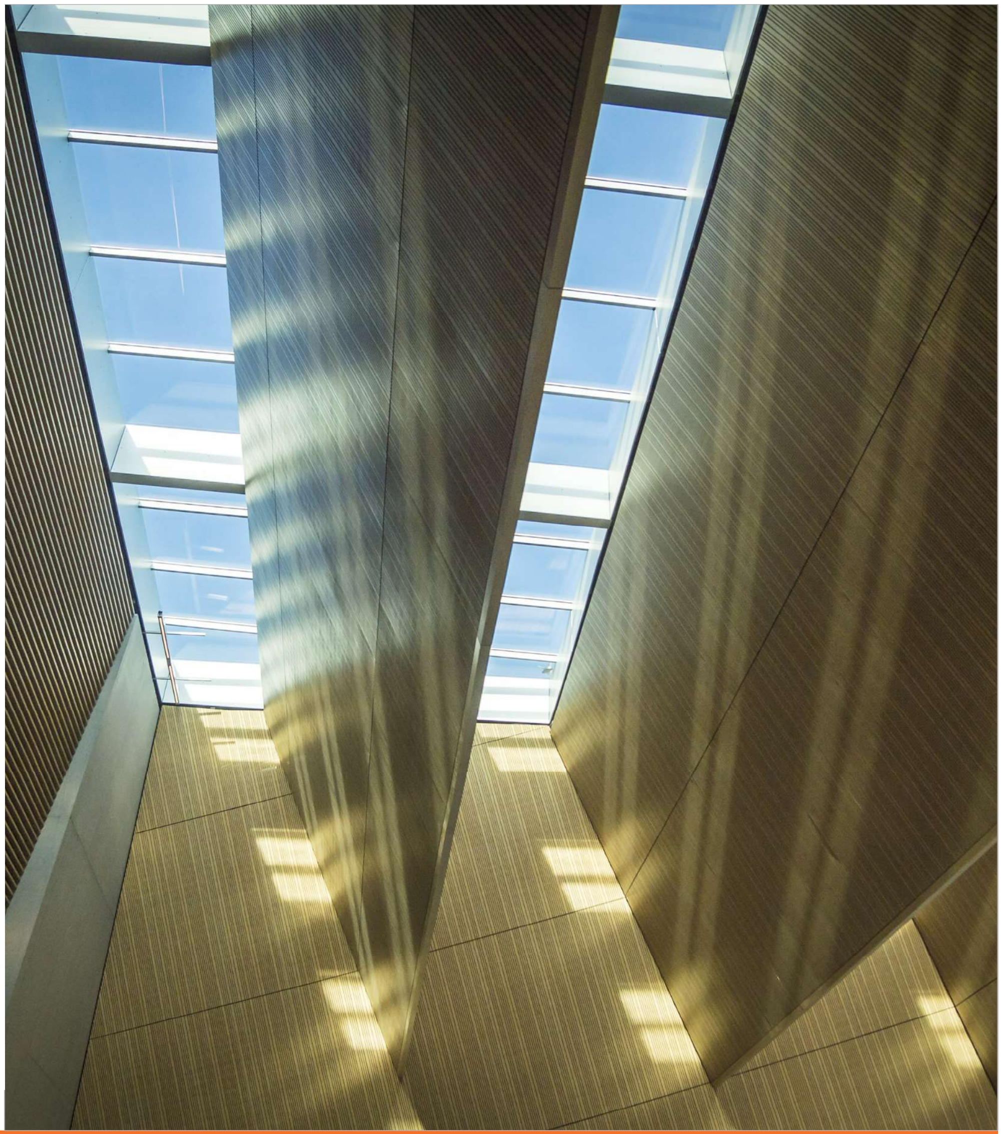

Proceedings of the 20th European Conference on Composite Materials

COMPOSITES MEET SUSTAINABILITY

Vol 2 – Manufacturing

Editors : Anastasios P. Vassilopoulos, Véronique Michaud

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ESCM EUROPEAN SOCIETY FOR COMPOSITE MATERIALS

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Edited By :

Prof. Anastasios P. Vassilopoulos, CCLab/EPFL
Prof. Véronique Michaud, LPAC/EPFL

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Editorial

This collection gathers all the articles that were submitted and presented at the 20th European Conference on Composite Materials (ECCM20) which took place in Lausanne, Switzerland, June 26-30, 2022.

ECCM20 is the 20th edition of a conference series having its roots back in time, organized each two years by members of the European Society of Composite Materials (ESCM).

The ECCM20 event was organized by the Composite Construction laboratory (CCLab) and the Laboratory for Processing of Advanced Composites (LPAC) of the Ecole Polytechnique Fédérale de Lausanne (EPFL).

The Conference Theme this year was “Composites meet Sustainability”. As a result, even if all topics related to composite processing, properties and applications have been covered, sustainability aspects were highlighted with specific lectures, roundtables and sessions on a range of topics, from bio-based composites to energy efficiency in materials production and use phases, as well as end-of-life scenarios and recycling.

More than 1000 participants shared their recent research results and participated to fruitful discussions during the five conference days, while they contributed more than 850 papers which form the six volumes of the conference proceedings. Each volume gathers contributions on specific topics:

Vol 1 – Materials

Vol 2 – Manufacturing

Vol 3 – Characterization

Vol 4 – Modeling and Prediction

Vol 5 – Applications and Structures

Vol 6 – Life Cycle Assessment

We enjoyed the event; we had the chance to meet each other in person again, shake hands, hold friendly talks and maintain our long-lasting collaborations. We appreciated the high level of the research presented at the conference and the quality of the submissions that are now collected in these six volumes. We hope that everyone interested in the status of the European Composites’ research in 2022 will be fascinated by this publication.

The Conference Chairs

Anastasios P. Vassilopoulos, Véronique Michaud

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And all those who helped, colleagues who reviewed abstracts and chaired sessions, and CCLab and LPAC students and collaborators who worked hard to make this conference a success.

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Composites Meet Sustainability – Proceedings of the 20th European Conference on Composite Materials,
ECCM20. 26-30 June, 2022, Lausanne, Switzerland

Manufacturing Advances for Pultruded Rod Based Structural Members and Thick Ply Systems

Laura Rhian Pickard[a], Giuliano Allegri[a], Michael R. Wisnom[a]

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Abstract: *Fibre-reinforced composite components based around pultruded rods are under investigation with the intention to deliver structural members with improved compressive performance compared to standard fibre-reinforced composites, through a novel hierarchical approach inspired by natural composites. These components present new challenges in manufacturing, as the cured rods become constituents in the larger composite parts. This work highlights advances in manufacturing two representative components, cylindrical struts and flat thick plies, each built around the rods. Key considerations are optimising rod alignment, manufacturing of suitably sized components for representative mechanical testing and minimising defects. Manufacturing methods for both of these components are presented and discussed.*

Keywords: Fibre-reinforced composites; pultruded rods; compression; infusion; prepreg

1. Introduction

Natural composites such as bamboo (Figure 1) or bone (Figure 2) are lightweight structures which perform well under compression. They have hierarchical structures, with features at multiple length scales. NextCOMP seeks to improve the performance of fibre-reinforced composites under compression by creation of similar hierarchical structures.

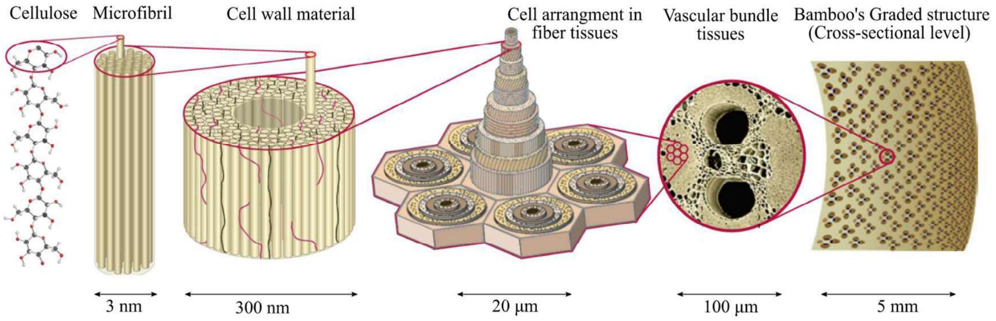

Figure 1. Illustration of hierarchical structure of bamboo. Reproduced from [1]

This work focuses on hierarchical composites based around pultruded carbon fibre-epoxy rods.

For a planar structure, rods must be organised into a flat thick ply. When infused in a channel and constrained at either end, rods are seen to flex between the ends, leading to misalignment. Therefore an adaptation of the 'prepreg sandwich' structure proposed by Clarke [2] is employed to keep the rods in place.

The sandwich structure is suitable for trialling rods of various diameters and cross sections. Using a resin film compatible with the prepreg, the structure may be cured in an autoclave. Use of thin-ply prepreg minimises the additional material.

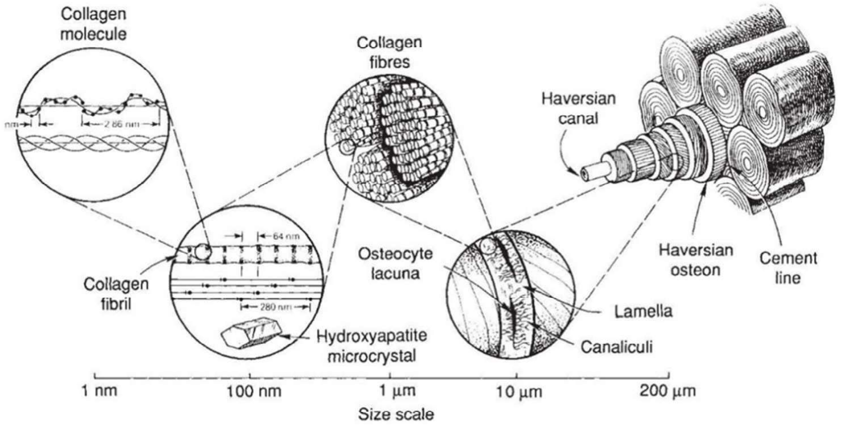

Figure 2. Illustration of hierarchical structure of bone. Reproduced from[3]

Wisnom [4] described use of an overwind on a solid carbon fibre-epoxy rod such as these to radially compress the rod in order to suppress splitting. Cylindrical struts, consisting of carbon-fibre epoxy pultruded rods of circular cross section plus an infused resin, were manufactured by Potter et al [5] for compression after impact testing. This work demonstrated that a Kevlar overwind around the strut could deliver improvement in compressive performance (Figure 3).

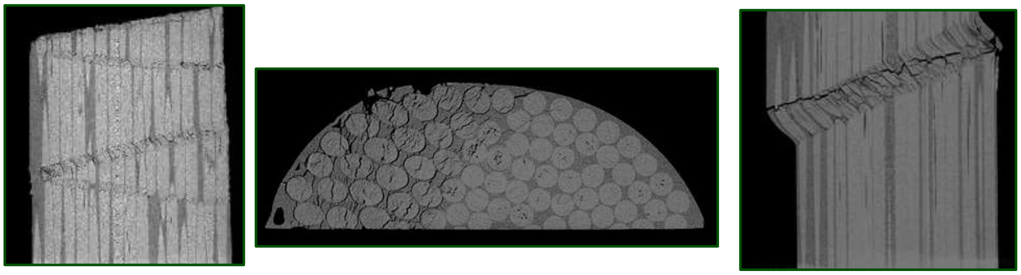

Figure 3. Samples from [5]*, CT scans L R Pickard. Following compression after impact tests. Overwound strut (left, showing zig-zag kink band propagation) exhibited greater compressive strength than without overwind (centre and right, showing single kink band)*

Similar cylindrical struts are discussed here, manufactured using different materials.

As we intend to construct a hierarchical composite, with layers of structure at different length scales designed to constrain compressive failure, individual pultruded rods may be overbraided, with the intention of ultimately using overbraided rods within structures such as cylindrical struts or thick plies.

2. Materials and manufacturing methods

While NextCOMP ultimately aims to incorporate novel fibres and resins; each with micro- or nano- structures designed to control compressive failure; into the hierarchical composites with ply and/or rod based higher level structures, for the initial development stage we use commercially available rods, resins and prepregs so that these can proceed in parallel.

2.1 Flat Thick Ply

Preliminary trials of infusion of loose, stitched and end-taped 'plies' of rods resulted in poor alignment and rolling of stitched groups of rods at the edge of infusion channels. Rods are sufficiently flexible to move during infusion despite constraint at the ends.

The 'prepreg sandwich' approach pioneered by Clarke [2], shown in Figure 4, requires rods to be precisely aligned between two layers of prepreg, with the addition of resin film between the rods to ensure wet-out.

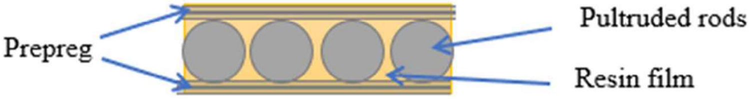

Figure 4. Diagram of 'prepreg sandwich' construction for thick ply containing pultruded rods

Manual lay-up of prepreg sandwich samples ~10cm in length each containing 15-20 rods was carried out using Hyperflight 0.7mm diameter carbon fibre-epoxy rods [6] and Skyflex K51 resin [7], with both Skyflex K51 unidirectional thin ply carbon fibre [7] and Hexcel 913 unidirectional E-glass [8] prepreg outer layers. The samples were cured in an autoclave for 90 minutes at 125°C, 7 bar pressure. The stated rod T_g is 170°C.

2.2 Cylindrical strut.

Cylindrical struts were manufactured using Easy Composites 0.8mm diameter carbon fibre-epoxy rods [9] and Prime 27 resin. Initial trials used a hollow glass tube of internal diameter 12.5mm, coated with release agent, as a tool. Rods were trimmed and fitted into the tool.

The glass tool was held vertically during infusion and cure, with the resin inlet at the base of the tool, to facilitate air bubbles rising to the outlet at the top. Infusion speed was manually controlled using clamps. Each strut was cured at 80°C for 4 hours in an oven.

Struts manufactured using flexible tubing followed the same method, with the addition of a vacuum bag surrounding the flexible tube to provide external radial compression.

2.3 Overbraiding

A Herzog 16 carrier microbraider, used at half capacity with 8 tows, was employed for overbraiding of 0.8mm diameter pultruded rods. A horngear rotary speed of 120±5 rpm was used and a variety of lay lengths tested. Lay length describes the length of braid constructed while a single tow travels a full 360° around the rod during the braiding process, so as lay length decreases braid angle is expected to increase. Overbraiding was carried out with Teijin Twaron 2200 aramid [10], Toyobo high modulus Zylon [11] and Toray T300 carbon fibre [12].

3 Results

3.1 Flat Thick Ply

Cured 'prepreg sandwich' thick plies retained rod alignment as shown in Figure 5. Microscopy (Figure 6) shows the Hyperflight rods contain voids and have an uneven fibre distribution. The rods have become ovalized during the cure, despite the temperature being lower than the stated rod T_g, and there are some gaps in rod spacing.

Figure 5. A cured thick ply prepreg sandwich: Skyflex K51 thin ply unidirectional carbon fibre, Skyflex K51 resin and Hyperflight 0.7mm diameter carbon fibre-epoxy pultruded rods

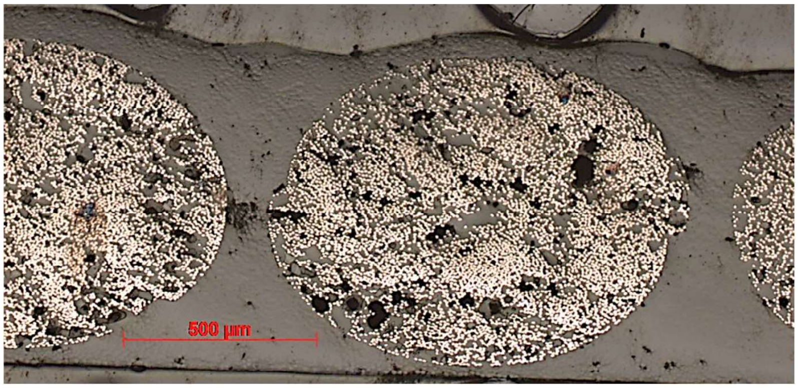

Figure 6. Microscope image showing rods between layers of 913 E-glass prepreg. Skyflex K51 resin film used between rods.

3.2 Cylindrical strut

Struts manufactured using a solid glass tube retain a circular cross section, however quality was variable (Figure 7). While the rods were packed tightly during setup, movement during infusion and cure was sufficient to result in non-uniform rod density. Voids were present throughout and racetracking between the rods and inner surface of the tube was seen, in one instance resulting in a large central void.

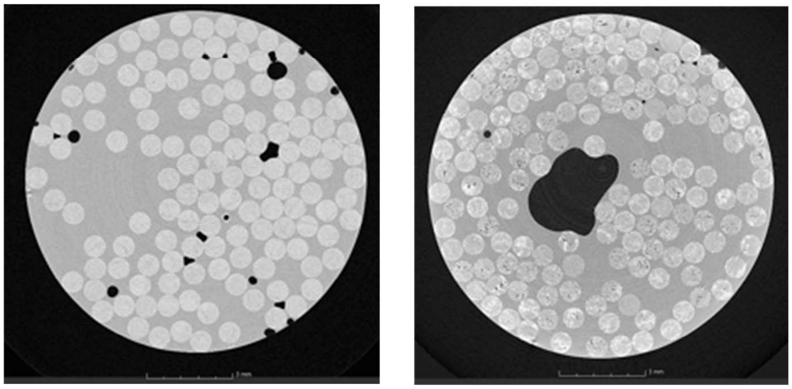

Figure 7. CT scan slices of struts manufactured using glass tools, 0.8mm diameter rods.

Struts manufactured using flexible tooling (Figure 8) showed much improved rod distribution and very little porosity. However the strut cross section was not circular.

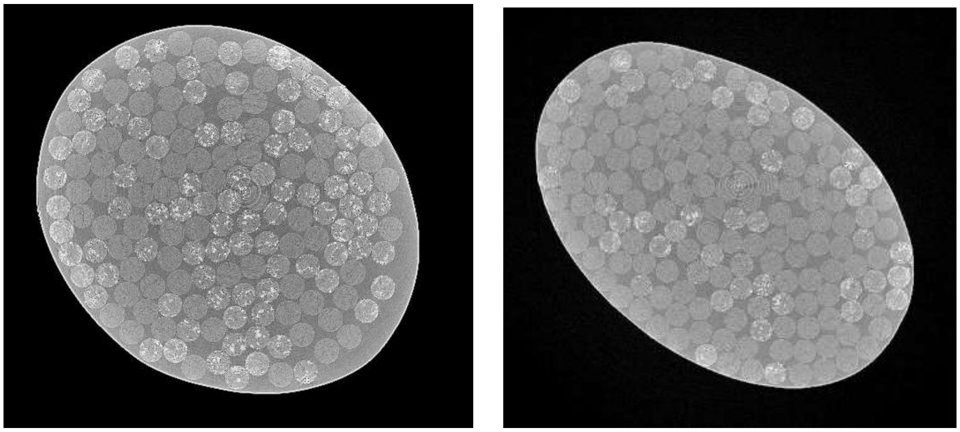

Figure 8. CT scan slices of struts manufactured using flexible tools, 0.8mm diameter rods.

3.3 Overbraiding

Overbraiding (Figure 9) of a relatively small diameter pultruded rod core requires small tows in order to achieve conformation to the rod at larger braid angles (shorter lay lengths). The aramid supplied, of 1610dtex, was too large to conform to a 0.8mm diameter rod at a lay length of 2mm causing bunching. However the braiding at this angle showed little fibre breakage, indicating this may be a suitable material in a smaller tow size.

For all materials, the input lay length was not always achieved in practice, with variation in braid angle and movement of the braid point seen.

273dtex Zylon showed relatively good conformation down to 1mm lay length, though braid angle was not consistent and some bunching was seen. No breakage was observed. A

1k T300 carbon fibre showed significant breakage, resulting in a ‘fuzzy’ overbraid with a minimum achievable lay length of 2mm, with only a small amount braided before tows snapped.

Figure 9. Overbraids of 0.8mm rod using 1K T300 carbon fibre at 2mm lay length (left), 273dtex high modulus Zylon at 1mm lay length (centre) and 1610dtex Twaron at 2mm lay length (right).

4. Discussion and next steps

Finite element modelling suggests that increased shear support in the matrix region between the rods may deliver improved compressive performance. The 'fuzzy' carbon overbraids may therefore be beneficial, as the broken fibres increase the effective interphase region and bridge the gaps between rods. A multi-material braid, combining zylon and carbon, may therefore be useful. Smaller tow sizes are to be trialled in overbraiding, and both single overbraided rods and the larger structures manufactured from them to be tested in compression. Reliable compression testing is also a challenge, with new methods under development by NextCOMP colleagues.

Thick plies can be made by hand in small sizes, using the prepreg sandwich model, however achieving precise rod alignment and sufficient resin content in larger samples becomes more difficult. We therefore propose to trial a human-robot collaborative approach, following the work of Elkington et al [13]. A robot can precisely place and hold components of the rod based composite while a human operator applies pressure to consolidate the part.

The work presented here is an initial step towards achieving manufacture of hierarchical, pultruded rod based composites. Future challenges will include integration of novel fibres and resins, which may have non-standard manufacturing requirements, into rod-based systems and integration of the struts and thick plies shown here into larger structures.

As a new way of thinking about composites, the hierarchical approach has the potential to change our approach to the design and manufacture of composite parts. This brings opportunities to develop novel architectures and the manufacturing techniques required to create them.

Improved performance under compression may expand the potential markets for composite products, and could deliver advantages in lightweighting and efficiency through redesign of existing systems. Future composites may not be restricted to the ply model, with rod-based structures among many options for the next generation of fibre-reinforced composites.

5. Conclusions

The two pultruded rod based systems discussed here, cylindrical struts and thick plies, are under development as demonstrators for the hierarchical approach.

Use of a flexible tool with vacuum bag when manufacturing cylindrical struts has been shown to deliver fewer voids and better rod density than a solid glass tool, where voids and racetracking between rods and the tool sides appear evident. Changes in tool fixings and/or post manufacture machining may be used to decrease the eccentricity of the resulting strut to achieve a circular cross section.

Simple infusion of a thick ply, with rods constrained outside the gauge section by stitching, results in poor alignment as the rods flex during infusion, and the stitched thick ply can roll at the edges of the infusion channel. A 'prepreg sandwich' approach, with rods between two layers of prepreg and the regions between rods packed with resin film has delivered better alignment at the proof of principle stage. The next stage of this work will involve trialling a human-robot collaborative approach to manufacture, intended to enable the repeatable manufacture of larger thick plies with precision.

Acknowledgements

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Supporting data can be requested from the corresponding author but may be subject to confidentiality obligations.

References

[1] T. Gangwar, D. J. Heuschele, G. Annor, A. Fok, K. P. Smith, and D. Schillinger, “Multiscale characterization and micromechanical modeling of crop stem materials,” *Biomechanics and Modeling in Mechanobiology*, vol. 20, no. 1, pp. 69–91, Feb. 2021, doi: 10.1007/S10237-020-01369-6/TABLES/5.

[2] A. Clarke, “Mechanical properties and process conversion of a novel form of unidirectional carbon fibre/epoxy rod.,” University of Bristol, 1998.

[3] R. Lakes, “Materials with structural hierarchy,” *Nature*, vol. 361, no. 6412, pp. 511–515, Feb. 1993, doi: 10.1038/361511a0.

[4] M. R. Wisnom, “Suppression of splitting and impact sensitivity of unidirectional carbon-fibre composite rods using tensioned overwind,” *Composites Part A: Applied Science and Manufacturing*, vol. 30, no. 5, pp. 661–665, May 1999, doi: 10.1016/S1359-835X(98)00174-2.

[5] K. D. Potter, F. Schweickhardt, and M. R. Wisnom, “Impact Response of Unidirectional Carbon Fibre Rod Elements with and without an Impact Protection Layer,” *Journal of Composite Materials*, vol. 34, no. 17, pp. 1437–1455, Sep. 2000, doi: 10.1106/3QGB-7PJ0-P129-4XRR.

[6] “0.8mm Carbon Rod - Materials.” https://www.hyperflight.co.uk/products.asp?code=CARBON-ROD-08MM&name=0-8mm-carbon-rod (accessed Apr. 12, 2022).

[7] “Green Chemicals Biz. SKYFLEX Team Materials Selection Guide SKYFLEX Prepreg,” 2014.

[8] “HexPly ® 913 125°C curing epoxy matrix Rheology Gel Time,” 2020, Accessed: Apr. 12, 2022. [Online]. Available: https://www.hexcel.com/contact

[9] “0.8mm Carbon Fibre Rod; 1m, 2m - Easy Composites.” https://www.easycomposites.co.uk/0-8mm-carbon-fibre-rod (accessed Apr. 12, 2022).

[10] "Twaron® Filament Yarn - Teijin Aramid." https://www.teijinaramid.com/en/product-details/twaron-filament-yarn/ (accessed Apr. 12, 2022).

[11] "ZYLON ® (PBO fiber) Technical Information (2005)."

[12] "T300-Technical-Data-Sheet-1.pdf".

[13] M. Elkington, C. Ward, A. Kirby, M. Libby, and N. Gandhi, "Collaborative Human-Robotic layup." Dec. 14, 2017. Accessed: Dec. 07, 2021. [Online]. Available: https://research-information.bris.ac.uk/en/publications/collaborative-human-robotic-layup