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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).

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.

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
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Vol 8. Special Sessions

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FUZZY OVERBRAIDS FOR IMPROVED STRUCTURAL PERFORMANCE

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Keywords: Hierarchical Composite, Overbraid, Compression, Microvascular Channels, Fuzzy Carbon

Abstract

Overbraiding is used as a reinforcement in two example systems. This includes both standard and 'fuzzy' overbraids, the latter created by braiding a brittle fibre at short lay length over a central component; when incorporated into a fibre-reinforced composite increases the resin-matrix contact zone. The fuzzy aspect is therefore expected to improve structural performance.

Hierarchical composites, inspired by nature, can be created using pultruded rods as an element, with a hierarchy of fibres at the shorter length scale forming rods at the medium scale and a larger structure then created from these rods. Overbraiding of the pultruded rods is shown to improve their performance under compression.

Microvascular channels, used for cooling, can be created in a composite laminate through a lost poly(lactic acid) process. Overbraiding of the poly(lactic acid) results in reinforced microvascular channels, with a fuzzy carbon overbraid demonstrating an order of magnitude increase in burst pressure of the microvascular channels compared to the unreinforced case.

1. Introduction

Micro-braiding is the combination of relatively small tows, yarns or rovings of fibre (hereafter 'tows' is used for brevity) into a small braid with diameter typically of millimetre scale. Overbraids contain a central core material. The properties of the braid are determined by the materials used and braiding parameters including the number of tows, braiding pattern and lay length of the braid. The lay length is the distance moved along the braid as one tow completes a full 360° revolution, illustrated in Figure 1.

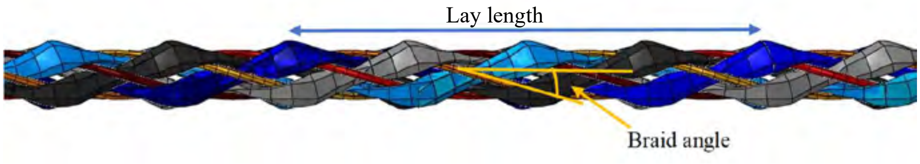

Figure 1. Illustration showing lay length (arrows) and braid angle. Created following method of O'Keeffe et al. [1]

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For an inner core of 0.7-0.8 mm diameter, 273 dtex poly(p-phenylene-2,6-benzobisoxazole) (PBO) [2] overbraids have been manufactured which conform tightly to the core at lay lengths of <2 mm, whereas 1k (660 dtex) T300 carbon fibre [3] overbraids were seen to undergo partial breakage at shorter lay lengths of 4mm or less, with the lowest achievable lay length being 2 mm [4]. The partial breakage resulted in strands of broken fibre extending away from the braid, giving a fuzzy appearance. Overbraids are expected to improve structural performance in the two cases discussed herein.

1.1 Compression: Pultruded rods for hierarchical composites

Fibre-reinforced composites are known for excellent performance under tension, leaving performance under compression as the limiting factor for many applications. Carbon fibre reinforced composites with a typical layered ply structure do not reflect the potential of the fibre itself under compression [5]. By contrast, natural composites can out-perform expectations based on their constituent materials [6]. These naturally occurring bio-composites utilise hierarchical structures [7], [8], with constituents at small scale combined to form structures which themselves are constituents at the next length scale, building up the hierarchy. An example, human compact bone, is shown in Figure 2.

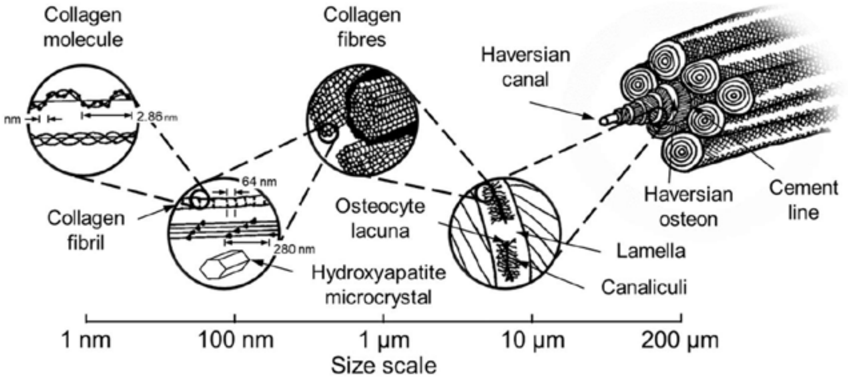

Figure 2. Illustration of the structure of human compact bone, a biological, hierarchical composite. Adapted from Lakes 1993 [9].

The NextCOMP programme [10] adapts this principle to create advanced fibre-reinforced composites with a hierarchical structure, by manufacturing composite structures using pultruded rods as components. Carbon fibre and epoxy resin are combined into pultruded rods- the smaller length scale- then these rods are used to make larger structures, as shown in Figure 3. These hierarchical composites are intended to achieve improved performance under compression compared to traditional approaches.

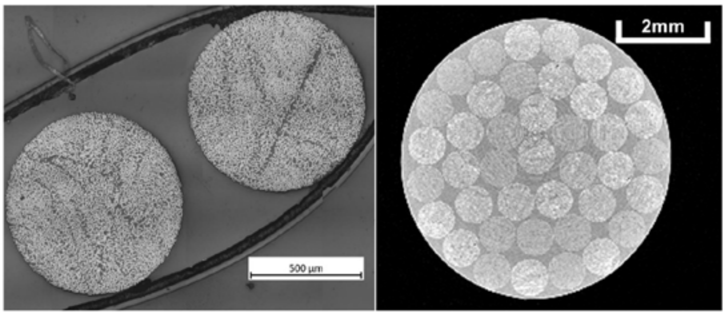

Figure 3. Hierarchical composites. Left: Cross section of pultruded carbon fibre-epoxy rods of 0.8 mm diameter [11]. Right: Slice from computerised tomography scan showing cured strut consisting of similar pultruded rods and second epoxy resin [12] manufactured by resin transfer moulding [13].

Overwinding of struts has been demonstrated to improve performance in compression and compression after impact [14]. Following the hierarchical approach, at the rod level micro-overbraiding was employed as illustrated in Figure 4. Overbraids are intended to suppress formation of kink bands in the rods by analogy to the overwound struts.

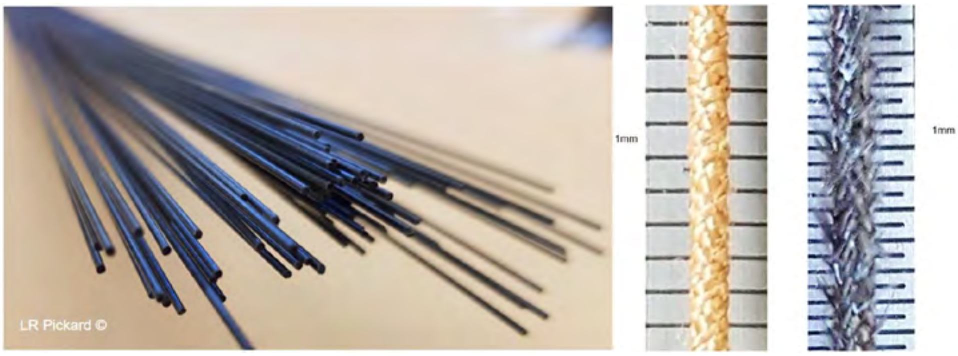

Figure 4. Micro overbraiding of pultruded rods. Left: carbon-fibre epoxy rods of 0.8 mm diameter. Centre: rod with 273 dtex PBO overbraid. Right: Rod with 1k T300 fuzzy carbon overbraid [4].

1.2: Burst pressure: Microvascular channels

Micro- overbraiding has also been utilised in reinforcing microvascular channels within a carbon fibre-epoxy laminate. The composite panels require embedded channels for cooling, intended for use in high energy physics applications. A target coolant pressure of 25 MPa was set for initial work. Laminates containing channels were manufactured by inclusion of a filament of poly (lactic acid) (PLA) which was vapourised post cure. These unreinforced channels failed below the target pressure through fracture in the resin rich region surrounding the channels [15], as shown in Figure 5.

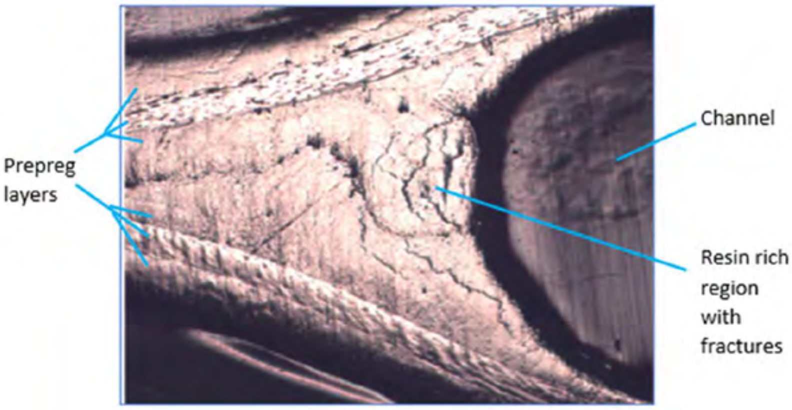

Figure 5. Microscope image showing fracture of microvascular channel following testing, modified from Dias et al. 2022 [15]

PLA filaments were reinforced with overbraids of aramid, carbon and short lay length carbon exhibiting the fuzzy geometry.

2. Materials and Methods

Overbraiding of both pultruded rods and PLA filaments was carried out using a Herzog 1/16/80 circular maypole microbraider at half capacity, 8 tows per braid. A simple diamond interlace pattern was used, with 4 tows passing clockwise around the braider and 4 tows anticlockwise, as detailed in [4].

2.1 Pultruded rods under compression

Pultruded rods [16] were tested with dry overbraids of 405 dtex High Elongation Twaron aramid with manufacturer specified modulus of 44-85 GPa [17] and 273 dtex high modulus Zylon™ PBO with manufacturer specified modulus of 270 GPa [2]. The dry overbraids are not fuzzy and, with no matrix wetting out the braid, the fuzzy behaviour seen with the carbon is not expected to be advantageous. This gives an indication of the improvement seen from overbraiding only, without any shear support.

The overbraided rods were tested using the 'cradle' 4 point bend method of Quino et al. [18], where the rod is bonded in a channel in the top of a polymethyl methacrylate (PMMA) cradle with a cut out unsupported gauge section, as in Figure 6. Under 4 point bending, the rod is loaded in compression.

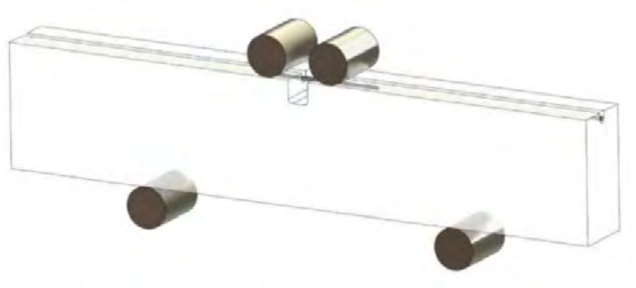

Figure 6. Test geometry, reproduced from Quino et al. 2022 [18].

Rods were then trialled with hybrid overbraids of fuzzy 1k T300 carbon with manufacturer specified modulus of 230 GPa [3] and HE Twaron aramid as above, fuzzy carbon and HM Zylon™ PBO as above, fuzzy carbon and basalt with manufacturer specified modulus of 90-100 GPa [19] with lay lengths ranging from 1 mm to 4 mm. The overbraids were wetted and cured using a resin bath of RS-M135 and hardener RS-MH137 [20] followed by in line ovens in a modified pultrusion system, and again tested using the geometry shown in Figure 6.

2.2 Burst pressure of microvascular channels

PLA filaments of 1.75 mm diameter were overbraided in 3 configurations:

- 1k T300 carbon fibre at 8 mm lay length, not fuzzy
- 405 dtex High Elongation Twaron aramid fibre at 2 mm lay length, not fuzzy
- 1k T300 carbon fibre at 2 mm lay length, fuzzy.

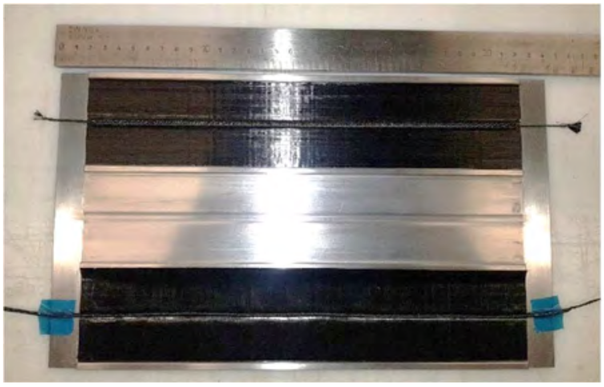

Figure 7. Lay-up of overbraided PLA filaments in test laminates. Lower plies and overbraided PLA shown on aluminium tool prior to addition of upper plies.

Overbraided, wrapped or plain PLA was laid up in a $[0,90,0]_s$ laminate of T800/ER450 unidirectional prepreg, with the PLA in the central plane of symmetry along the 0° axis, as shown in Figure 7. Paired with a flexible silicone top and vacuum bagged, the assembled laminates were cured in an autoclave at 4 bar pressure following the recommended cycle of 30 min at 80 °C followed by 3 h at 135 °C. Following cure the panels were trimmed and the PLA vaporised in an oven at 200 °C, leaving panels with embedded microvascular channels. This work is reported in detail by Dias et al.[21].

The burst pressure of the microvascular channels was tested by injection of water. Needle connectors were adhered to each end of the channel, with one connected to a closed valve and the other to a water inlet. Water was added using a pump, slowly increasing the pressure until the burst point was reached.

3. Results

3.1 Pultruded rods under compression

Dry fibre overbraids were shown to improve the load at failure by 65% for the aramid case and 70% for the PBO case compared to plain rods without an overbraid, as shown in Table 1. 3 tests of the plain rods were carried out and 5 of each overbraided type, with one aramid and two PBO samples excluded from the summarized results due to anomalous behaviour suggesting invalid failure.

Table 1. Results of testing pultruded rods with dry overbraids under compression

Specimen type	Mean load at failure (kN)	Standard deviation (kN)
Plain rods	2.96	1.02
Dry aramid overbraid	4.88	0.51
Dry PBO overbraid	5.02	0.29

Carbon and basalt overbraids were both seen to form a fuzzy structure, with the basalt broken strands being ~1cm long and far fewer in number compared to the ~1 mm long carbon broken strands.

Hybrid carbon/aramid and carbon/PBO overbraids showed fuzzy geometry from the carbon at lay length of 3 mm and below. Hybrid carbon/basalt overbraids showed fuzzy geometry from both materials at 1 mm-4 mm lay length.

Rods with wetted and cured fuzzy overbraids were tested following the same method as the dry overbraids. In this case the PMMA cradle failed before the overbraided rod, implying a significant improvement in performance but this could not be measured with the existing test. This is discussed further by Darras et al. [22].

Nwuzor et al. [23] integrated rods of 0.8 mm diameter with various overbraids, including short lay length fuzzy carbon, into struts following the pressurised resin transfer moulding method [13]. The fuzzy overbraids were seen to impregnate fully as shown in Figure 8. No porosity was detected in the resin or overbraids.

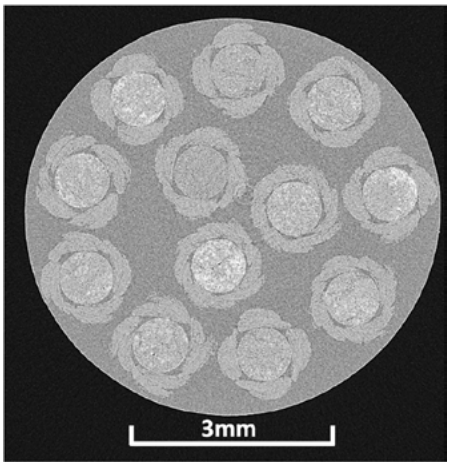

Figure 8. Slice from X-ray CT scan of 6 mm diameter strut containing pultruded rods with fuzzy carbon overbraids. Modified from Nwuzor et al. 2024 [23].

3.2 Burst pressure of microvascular channels

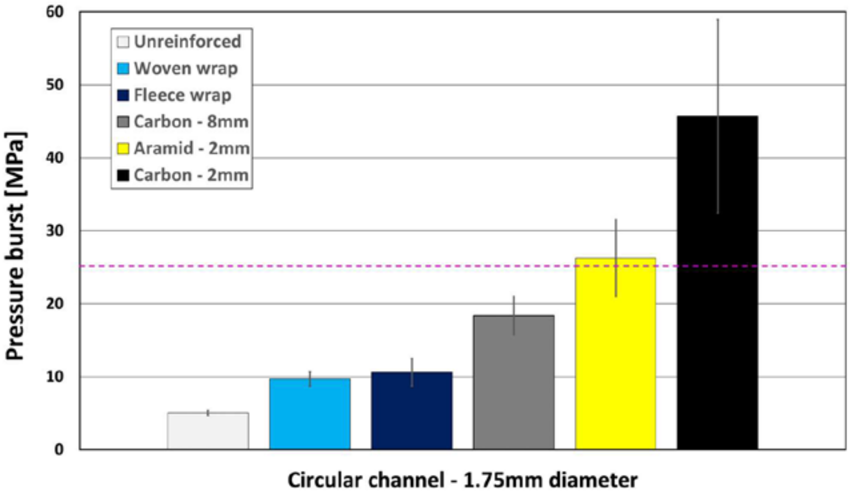

Figure 9. Burst pressure of microvascular channels with different reinforcements.

The results of the burst pressure tests are shown in Figure 9, with three samples of each overbraid type included in the analysis. All reinforcements delivered an improvement over the unreinforced case. Further, all three of the overbraided reinforcements outperformed the alternative reinforcements, created by wrapping the PLA in either 2 layers of carbon fleece plus a layer of ER450 resin film (fleece wrap); or a single ply of T300/ER450 plain weave prepreg (woven wrap).

The 2 mm lay length aramid overbraid case shows an increase in burst pressure of 520% compared to the unreinforced case and the 8 mm lay length carbon overbraid case shows an increase of 360%. Neither of these exhibit the fuzzy characteristic.

The 2 mm lay length carbon fuzzy overbraid delivers the highest burst pressure, with an increase of ~1000% compared to the unreinforced case. Numerous samples with fuzzy carbon overbraid reinforced channels did not reach burst pressure due to failure of the injection system before the microvascular channel. Further results and more detailed discussion are presented by Dias et al. [21].

4. Discussion

These two examples demonstrate the utility of overbraiding for reinforcement in their very different load cases. Braids without a fuzzy aspect have been shown to improve both compressive performance of pultruded rods and burst pressure of microvascular channels. The improvement is far greater in the latter case, where the braids are wetted and cured rather than dry.

Fuzzy braids show markedly greater performance than braids without a fuzzy aspect. In the microvascular channel case, inclusion of a 2 mm aramid braid- the same lay length as the fuzzy carbon 2 mm braid- and an 8 mm carbon braid- the same material, but different lay length to avoid fuzzy behaviour- provide reasonable comparisons, supporting the assertion that the fuzzy aspect delivers improved structural performance. In both trial cases the fuzzy overbraids outperformed initial test methods necessitating redevelopment of the tests.

The reinforced microvascular channels, while developed with high energy physics in mind, have the potential to be used in a wide range of applications, for example thermal control in a lightweight system may be applicable in the space sector and in casings for EV batteries and motors.

Hierarchical composites are a novel approach and show great promise in delivering improved performance under compression, likely to be useful in civil engineering, rocketry, wind turbines and many other applications where compressive performance is crucial. The pultruded rod approach facilitates the use of overbraiding to improve mechanical performance and integration of overbraided rods into larger structures has been demonstrated.

5. Conclusion

Overbraiding has delivered improved performance for pultruded rods under compression and microvascular channels with interior pressurization. Braids with a ‘fuzzy’ aspect, created using a brittle fibre at short lay length, show significantly greater improvement than non-fuzzy braids in the latter case.

Acknowledgments

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References

[1] C. O’Keeffe, L. R. Pickard, J. Cao, G. Allegri, I. K. Partridge, and D. S. Ivanov, “Multi-material braids for multifunctional laminates: conductive through-thickness reinforcement,” *Funct. Compos. Mater.*, vol. 2, no. 1, 2021, doi: 10.1186/s42252-021-00018-0.

[2] Toyobo, “ZYLON ® (PBO fiber) Technical Information (2005).” https://www.toyobo-global.com/seihin/kc/pbo/zylon-p/bussei-p/technical.pdf (accessed May 08, 2024).

[3] Toray, “T300-Technical-Data-Sheet-1.pdf.” https://www.toraycma.com/wp-content/uploads/T300-Technical-Data-Sheet-1.pdf.pdf (accessed May 08, 2024).

[4] L. R. Pickard, G. Allegri, and M. R. Wisnom, “Overbraiding of Pultruded Rods for Hierarchical Composites,” *Proceedings of the 23rd International Conference on Composite Materials*, 2023. https://www.iccm-central.org/Proceedings/ICCM23proceedings/papers/ICCM23_Full_Paper_348.pdf

[5] M. Ueda and M. Akiyama, “Compression test of a single carbon fiber in a scanning electron microscope and its evaluation via finite element analysis,” *Adv. Compos. Mater.*, vol. 28, no. 1, pp. 57–71, 2019, doi: 10.1080/09243046.2018.1433506.

[6] M. A. Meyers, J. McKittrick, and P. Y. Chen, “REVIEW Structural Biological Materials: Critical Mechanics-Materials Connections,” *Science (80-.).*, vol. 339, no. February, pp. 773–780, 2013, doi: 10.1126/science.1220854.

[7] P. Y. Chen, J. McKittrick, and M. A. Meyers, “Biological materials: Functional adaptations and bioinspired designs,” *Prog. Mater. Sci.*, vol. 57, no. 8, pp. 1492–1704, 2012, doi: 10.1016/j.pmatsci.2012.03.001.

[8] D. Nepal *et al.*, “Hierarchically structured bioinspired nanocomposites,” *Nat. Mater.*, vol. 22, no. 1, pp. 18–35, 2023, doi: 10.1038/s41563-022-01384-1.

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

[10] NextCOMP, “Next Generation Fibre-Reinforced Composites: A Full Scale Redesign for Compression,” *www.nextcomp.ac.uk*.

[11] “0.8 mm Carbon Fibre Rod; 1 m, 2 m - Easy Composites.” https://www.easycomposites.co.uk/0-8mm-carbon-fibre-rod (accessed Apr. 12, 2022).

[12] Gurit, “Full General Datasheet PRIME TM 27 Epoxy Infusion System” https://www.gurit.com/wp-content/uploads/2022/12/prime-27.pdf (accessed May 08, 2024).

[13] L. R. Pickard, J. Crinson, N. Darras, G. Allegri, and M. R. Wisnom, “Evaluation of manufacturing methods for pultruded rod based structural members with minimal porosity,” *J. Plast. Rubber Compos. Macromol. Eng.*, vol. 53, no. 1, pp. 25–35, 2024, doi: 10.1177/14658011231212627.

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

[15] M. Dias, D. A. Feito, F. Boyer, A. Catinaccio, C. Gargiulo, and P. Olivier, “Pressure resistance characterisation of micro-vascular networks embedded in carbon composites for High Energy Physics applications,” in *20th European Conference on Composite Materials*, 2022, pp. 531–538. doi: 10.5075/epfl-298799.

[16] “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).

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

[18] G. Quino, P. Robinson, and R. S. Trask, “Design of a bending experiment for mechanical characterisation of pultruded rods under compression,” in *20th European Conference on Composite Materials,* 2022, doi: https://doi.org/10.5075/epfl-298799_978-2-9701614-0-0.

[19] “Basalt Roving - Deutsche Basalt Faser.” https://www.deutsche-basalt-faser.de/en/products/basalt-roving/# (accessed Apr. 29, 2024).

[20] PRF Composites, “Epoxy Resin Systems Product Data Ultra Low Viscosity Epoxy System Hardeners RS-MH134 & RS-MH137.” https://www.prfcomposites.com/sites/default/files/resources/RS-M135 3.3 Jun 2019 TDS012.pdf (accessed May 08, 2024).

[21] M. Dias *et al.*, “Pressure resistance characterisation of vascular networks embedded in carbon composites for high energy physics applications.,” *Compos. Part B*, vol. 282, 2024, doi: 10.1016/j.compositesb.2024.111535.

[22] N. S. T. Darras *et al.*, “Investigation of the Internal Structure Configuration of Hierarchical Composites and its Impact on their Mechanical Compressive Performance,” *Proceedings of the 21st European Conference on Composite Materials*. Nantes, France, 2024.

[23] I. Nwuzor *et al.*, “Integrating Fiber Overbraids in Composites for Enhanced Compressive Performance,” *Proceedings of the 21st European Conference on Composite Materials*. Nantes, France, 2024.

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