Composites Part C: Open Access 14 (2024) 100447

Contents lists available at ScienceDirect

Composites Part C: Open Access

journal homepage: www.elsevier.com/locate/composites-part-c-open-access

Mechanical analysis of a carbon fibre composite woven composite laminate for ultra-light applications in aeronautics

Nicholas Fantuzzi [a],[*], Antoine Dib [a], Sajjad Babamohammadi [a], Silvio Campigli [b], David Benedetti [c], Jacopo Agnelli [c]

[a] *DICAM Department, Viale del Risorgimento 2, Bologna, 40136, BO, Italy*
[b] *Microtex Srl, Via del Pozzo San Sebastiano 15/c, Pistoia, 51100, PT, Italy*
[c] *Carbon Dream SpA, Via Fausto Melotti 16, Barberino Tavarnelle, 50028, FI, Italy*

ARTICLE INFO

Keywords:
Ultra-light carbon-based composite
Aeronautical industry
Finite element modeling
Finite element method

ABSTRACT

Carbon fiber composites have emerged as a transformative technology, offering a fascinating alternative to traditional materials like aluminum and steel. Their unique combination of high strength, stiffness, and reduced density makes them an ideal choice for lightweight structural components, an attribute that aligns with the pursuit of fuel-efficient and eco-friendly aircraft designs. With the continuous race between countries and research organizations to find new materials that satisfies the above-mentioned characteristics, this article highlights the utilization of a new Ultra-Light Carbon-based Composite (ULCC) in the aeronautical sector developed within the industrial research project TERSA (Radar technologies for autonomus flying vehicles or TEcnologie Radar per Sistemi aerei a pilotaggio remoto (SAPR) Autonomi in italian). The composite material has been developed with the aim of achieving superior performance and efficiency compared to existing products on the market. To evaluate its effectiveness, first, the mechanical properties of the ULCC have been compared to T300/Epoxy and T1000/Epoxy, two of the materials commonly used in aeronautical industry and unmanned aerial vehicle (UAV). Second, finite element models were employed to verify and analyze the dynamic properties of aeronautical structural components made of ULCC. The results indicate that the new carbon-based composite exhibits remarkable strength-to-weight ratio, enhanced durability, and offering significant advantages in terms of weight reduction and overall performance. These findings validate its potential as a viable alternative in aeronautical industry.

1. Introduction

Throughout history, the progression of materials technology has had a profound impact on the growth and sophistication of societies. Early civilizations were called stone ages because human primarily used materials like stone, wood, bone, etc. Bronze Age that was characterized by the widespread use of bronze (a copper-tin alloy), brought about improved weapons, tools, and artwork. The Iron Age saw the rise of iron-working techniques used for tools, weapons, and infrastructure. The modern era witnessed the development of very high number of new materials like plastics, composites, and semiconductors, which revolutionized industries ranging from aerospace and electronics to health-care. Nanomaterials and nanotechnology have opened up new possibilities in medicine, electronics, and materials science. Moreover, the aeronautic industry required the development of advanced materials for spacecraft, spacesuits, and satellite technologies. Indeed, it has undergone remarkable transformations in recent years, driven by a relentless pursuit of enhanced performance, efficiency, and sustainability. The advancement in aerospace materials encompass a wide range of factors, including cost reduction, weight reduction, increased strength, enhanced toughness, improved durability [1] and reducing fuel consumption. Carbon fiber composite woven laminate is such material that has garnered considerable attention, especially for its exceptional strength-to-weight ratio and potential for ultra-lightweight applications in aeronautics. Since the use of advanced polymer composite for the first time in 1953 in a commercial production by the Chevrolet Corvette car, both automotive and aerospace industries are in non-stop research to optimize and introduce such new materials [2,3]. In the 1960s, the United States National Aeronautics and Space Administration (NASA) began exploring the use of carbon composites for aerospace applications [4]. In 1963, the Boeing 727 incorporated carbon composites in the vertical stabilizer and rudder [5]. 15 years later, the General Dynamics F-16 fighter jet presented composite wings with carbon fiber reinforcement [6]. In a commercial level, many aircrafts incorporate

---

[*] Corresponding author.
E-mail address: nicholas.fantuzzi@unibo.it (N. Fantuzzi).

https://doi.org/10.1016/j.jcomc.2024.100447
Received 14 December 2023; Received in revised form 12 February 2024; Accepted 27 February 2024

carbon composites in vital elements of the planes, like Airbus A310 that was the first commercial aircraft to incorporate carbon composites in the vertical tail plane in 1983 [7–9] or the Boeing 777 that featured composite empennage components, including the horizontal stabilizer and vertical fin in 1995 [5]. The Boeing 787 Dreamliner, introduced in 2011, marked a significant milestone with its extensive use of carbon composites in the fuselage, wings, and empennage [10–12]. Carbon composites have also made substantial contributions to military aircraft. The Lockheed Martin F-22 Raptor, introduced in 2005, incorporated carbon composites for major structural components, resulting in reduced weight and improved maneuverability [13]. Similarly, the Lockheed Martin F-35 Lightning II, which extensively employed carbon composites in 2006, benefited from stealth capabilities and weight reduction [14]. In parallel, carbon fiber composites have had a significant impact on the market of drones, bringing about notable changes and advancements, in terms of weight reduction [15] compared to traditional materials like aluminum, which improves drone performance, including flight time, maneuverability, and payload capacity [16]. Carbon composites also exhibit excellent resistance to fatigue, corrosion, and environmental conditions, increasing the reliability and longevity of drones while reducing maintenance requirements [17,18]. Furthermore, their design flexibility enables innovative drone designs [17] and integration of advanced features like embedded sensors, antennas, and electronics within the composite layers [19,20]; all these features are insured without jeopardizing the structural integrity that, in contrary, has been enhanced since the carbon fiber composites exhibit exceptional stiffness and rigidity that contributes to better aerodynamic performance, stability, and responsiveness during flight [20,21].

The world of research has been always closely interconnected with the aeronautic industry in the journey of implementing carbon fiber components, through verifying or developing novel carbon fiber composition and use. For instance, researchers are exploring novel carbon fiber reinforcements to enhance the mechanical properties and performance of carbon composites, including high-strength carbon fibers, carbon nano-tube reinforced fibers [22,23]. Others are exploring novel carbon fiber reinforcements to enhance the mechanical properties and performance of carbon composites [24,25]. This includes the development of high-strength carbon fibers, such as ultra-high modulus fibers and carbon nanotube-reinforced fibers. The development of automated manufacturing processes, such as automated fiber placement and robotic-assisted manufacturing is the topic of research followed by some others [22,26,27]. While the use of hybrid composites, which combine carbon fibers with other reinforcing materials like ceramics or metals, is gaining attention to achieve a balance between strength, weight reduction, and enhanced damage tolerance with reference to laboratory tests [28,29], other researchers are employing advanced computational modeling and simulation techniques to predict and optimize the behavior of carbon composites, especially through Finite element analysis (FEA) [30–32].

Regarding the last point, the validity of carbon-based composites for aerospace applications is verified through a rigorous process that involves extensive testing, analysis, and certification. The first Key aspect of the verification process is the material characterization where carbon composites undergo tests to assess their mechanical properties, such as tensile strength, bending strength, and impact resistance. Second step is the simulation of the structural behavior of carbon-based composites under various load conditions through finite element analysis or FEA. FEA helps evaluate factors such as natural frequency, stress distribution, deformation, and failure modes, providing valuable insights into composite performance. After that the new proposed material pass the test of FEA and to ensure the validity of the new composite, a full-scale structural testing is conducted. The last step is to meet stringent certification requirements and comply with industry regulations including mechanical properties, manufacturing processes, structural integrity and safety. A following step in the verification of the UAV is the maintenance and reparation of the aircraft once entered in function, but this is another different topic behind the aim of this article [33].

Within the scope of the actual industries to harness the potential of renewable resources and prioritize the utilization of recyclable materials and materials with a reduced global footprint [34], the aim of this paper is to introduce a new ultra-light carbon-based composite (ULCC) engineered for deployment in ultra-light applications within the aeronautics sector, more specifically, the market of unmanned aerial vehicle (UAV) known as a drone. Hence, since it is a new material, it has been investigated its mechanical properties and its structural simulation. The research is divided into two-fold: in first place, the evaluation of the mechanical properties of the woven laminate, and in a second place, the assessment of its suitability for integration into next-generation aircraft designs aimed at achieving unprecedented levels of fuel efficiency and performance through FE models. The mechanical characteristics of the ULCC have been compared to two different carbon fiber composite woven laminates: T300/Epoxy, T1000/Epoxy. The comparison, through Finite Element models, of different components of the newly designed drone, underscores the potential advantages and challenges associated with the adoption or choice of one of these advanced composite materials in the industry.

2. Background

In recent years, there has been a significant increase in the utilization of Unmanned Aerial Vehicles (UAVs), also known as drones. This technology has found application across various fields due to its ability to access challenging and hard-to-reach areas with ease [35]. The TERSA project aims to develop technologies for electric propulsion on SAPR (Remotely Piloted Aircraft System) with take-off weight less than 35/50 kg. The expected result of the project significantly increases the dual operational capabilities of surveillance, control and data collection both on land and at sea, as well as the ability to be integrated into civil air traffic while also ensuring a low environmental impact. In particular, two configurations are being studied, one with a conventional fixed wing and one with a VTOL fixed wing, both of which can be equipped with an electric propulsion system and a Sense and Avoid (S&A) system suitable for inserting the aircraft into air traffic. A newly carbon fiber material, regarding the square meter weight of the fabric, percentage of resin used in the prepreg and times, cycle, pressure and temperature in the autoclave, Young's and Tensile modulus strength, has been manufactured for this project. Composite materials destined to aerospace products have to withstand many requirements, which do not limit to mechanical properties only. Compatibility with hydrocarbons, maintaining the same properties at a wide range of temperatures including extremely low temps, avoiding developing micro-cracks within the polymer matrix, etc. For the sake of project confidentiality, the authors are report the data that can be shown in the current funded applied research.

2.1. The material

A conducted study was aimed at defining the fabric production processes and subsequent vacuum bag forming of carbon and epoxy resin-based prepreg composites. The objective was to create from scratch (as it did not exist on the market) a very low weight prepreg fabric: 65 g/m^2 with a 47% of epoxy resin. An adequate compromise between performance, costs and polluting emissions has been identified.

The material used is pre-preg carbon fiber with an epoxy matrix. Among the most common resin systems like vinylester, polyester, etc., epoxy provides the best mechanical performance although being more expensive. The fabric layers are pre-impregnated, meaning that the plies have a given resin content and the laminate needs to receive temperature and pressure to activate and consolidate the polymerization process.

Table 1
Composites properties.

	T300/Epoxy	T1000/Epoxy	ULCC
E (GPa)	128.0	163.2	240
ρ (t/m^3)	1.535	1.557	1.557

All prototype models of the pieces that make up the fuselage of the aircraft were created, also managing to understand how to reduce variability, in order to guarantee industrial repetitiveness of the characteristics of an ISO 9100 certified aeronautical product.

Standard quality control testing being carried on incoming materials are the differential scanning calorimetry (DSC) aimed to verify the residual degree of polymerization of the resin matrix, plus a visual inspection of the pre-preg aimed to confirm the absence of defects on the fabric. Further tests to carry out are the mechanical characterization of the materials (destructive on specific specimens), the Dynamic Mechanical Analysis (DMA), which is a technique aimed to analyze the cured sample's kinetic properties by measuring the strain or stress of a given cured sample, tapping aimed to make an expedite check for possible delamination, until the Ultra Sound (US) check, also aimed to intercept delamination.

2.2. Homogenization

For better comparison, the material has been compared to two conventional materials, commonly used in the aerospace industry: T300/Epoxy and T1000/Epoxy [36]. To obtain the mechanical properties of these composites, the rule of mixture has been applied with the same volume percentage reported in material data sheets: the volume fractions for the fibers and the matrix are $V_f = 0.55$ and $V_m = 0.45$, respectively. T300/Epoxy and T1000/Epoxy properties are provided by the supplier as picked from its database, while ULCC properties have been determined by rule of mixture. The mechanical properties of each phase of these composites are reported in [36] and the mechanical properties of homogenized composites are reported in Table 1.

3. Modeling

Finite Element (FE) models were developed and analyzed to examine the dynamic properties of the structures manufactured with three composites: T300/Epoxy, T1000/Epoxy and ULCC.

The decision to carry out free vibrations was aimed to test the overall dynamic behavior of the components (meaning geometry, laminate, materials, etc.) to validate the aircraft design, rather than testing just the composite properties alone. In case of major discrepancy between the result and the model, specific corrective action had to be defined and applied.

The number of models corresponds to the analysis of 3 distinct structural elements, with each element being individually examined using the three materials (CAD model of such elements are depicted in Fig. 1). The 3 studied elements are named:

1. Boom support inner
2. Boom support outer
3. Electric motor nose frame

The first two items represent the inner and outer support for the UAV boom, respectively, and the third one is the nose of the electric powertrain of the UAV. The requirements of such components were defined during the design phase: high-strength and stiffness had to be considered.

In the following calculations each element is made up of 24 plies of 0.12 mm thickness and in each model, pinned constraints at the edge of the bolted holes have been considered. All models have been developed in ABAQUS software. The choice of ABAQUS was made due to its delivery of precise results, computational efficiency, and advanced capabilities for handling complex 3D models. Additionally, the S4R/S3R plate/shell finite elements are being employed as they are recommended by the documentation for their reliability.

Table 2
Boom support inner frequencies.

	Frequency (cycles/time)					
	1	2	3	4	5	6
T300/Epoxy	21.06	52.22	77.63	116.69	133.08	179.25
T1000/Epoxy	23.61	58.55	87.03	130.83	149.20	200.97
ULCC	28.63	70.99	105.54	158.65	180.93	243.71

Table 3
Boom support outer frequencies.

	Frequency (cycles/time)					
	1	2	3	4	5	6
T300/Epoxy	21.17	52.04	77.94	117.61	132.55	180.62
T1000/Epoxy	23.74	58.34	87.38	131.86	148.61	202.50
ULCC	28.79	70.75	105.96	159.90	180.22	245.57

Table 4
Electric motor nose frame frequencies.

	Frequency (cycles/time)					
	1	2	3	4	5	6
T300/Epoxy	283.37	316.84	335.56	400.46	511.18	532.67
T1000/Epoxy	317.70	355.22	376.22	448.98	573.11	597.20
ULCC	385.27	430.77	456.23	544.46	695.00	724.22

3.1. Boom support inner

The first 6 natural frequencies of the inner boom support are listed in Table 2. When the ULCC material is employed, the highest frequencies are observed with a substantial increment in the stiffness structural component. This is due to the fact that ULCC possesses the highest elastic modulus compared to the other materials by keeping the same density. The elasticity Modulus of ULCC material is 87.5% higher than conventional T300/Epoxy while the density increases by approximately 1.5% only. The graphical representation of first 6 mode shapes are represented in Fig. 2.

3.2. Boom support outer

The present structural component should support the boom in cooperation with the inner support. Therefore the two components of different geometry should have similar dynamic characteristics. In fact as provided in Table 3 frequencies are in line with the ones previously shown in Table 2. In the present case also the ULCC shows a higher stiffness and structural mode shapes depicted in Fig. 3 are analogous to the former ones (Fig. 2). Both structure have a similar behavior of a simply-supported beam of not uniform cross-section, thus, such dynamic behavior was expected by the designers.

3.3. Motor nose frame

The last analyzed component is a nose frame support structure for the electric power train of the UAV. The shape of such structure is a combination of a conical shell with a circular plate bolted at the base of the cone and free at the top. The first 6 natural frequencies are listed in Table 4 for the considered materials and the effect of using ULCC is evident especially at higher modes when the different is around +36%. The first 6 mode shapes have been depicted in Fig. 4 where the effect due to boundary conditions for the present structure is clearly visible.

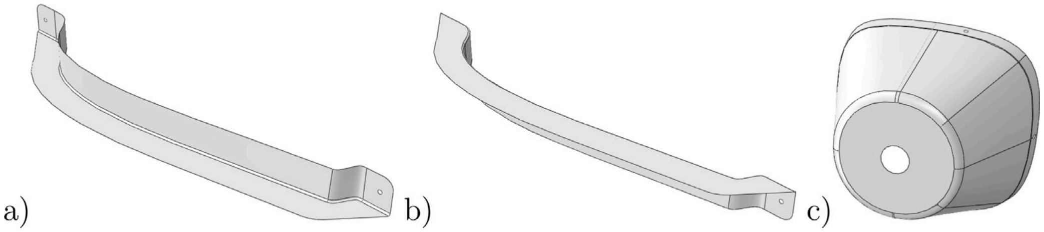

Fig. 1. CAD models analyzed: (a) boom support inner; (b) boom support outer; (c) electric motor nose.

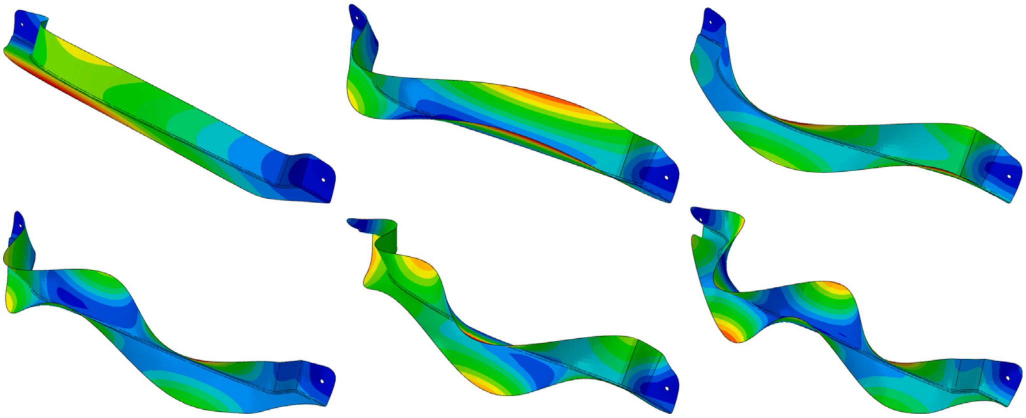

Fig. 2. First 6 mode shapes of the boom support inner component.

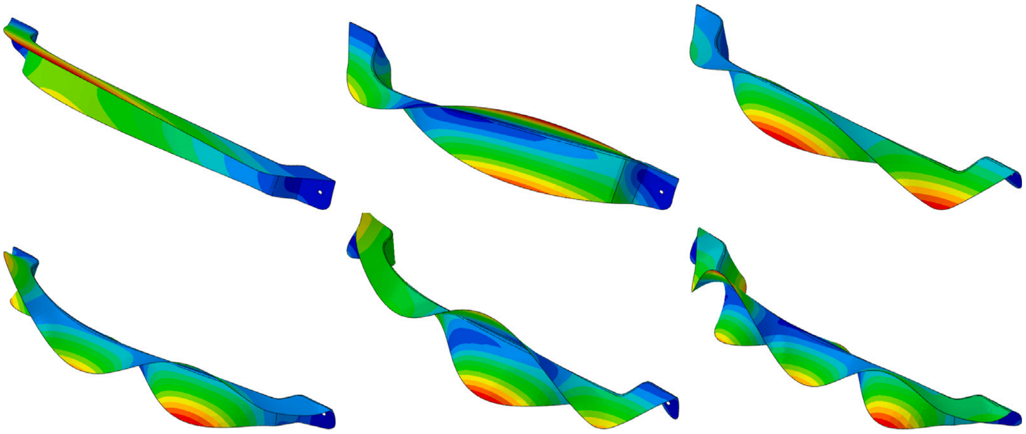

Fig. 3. First 6 mode shapes of the boom support outer component.

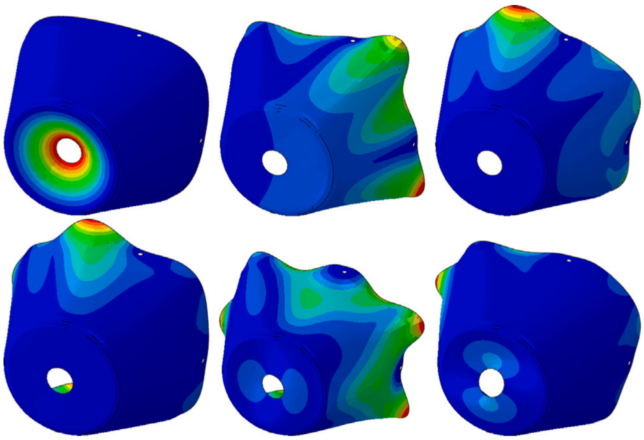

Fig. 4. First 6 mode shapes of the motor nose frame.

4. Conclusion

This paper introduces a novel ultra-light carbon-based composite (ULCC), which has been developed for potential use in the aeronautical industry. A comparative analysis was conducted between ULCC and two conventional materials commonly used in similar aircrafts, namely T300/Epoxy and T1000/Epoxy. The results reveal that the new ULCC exhibits higher stiffness and lower density, offering advantages in the realm of aerospace applications. To further evaluate the feasibility of implementing ULCC in the industry, Finite Element models were employed for verification. The findings indicate that the new ULCC shows great promises as innovative material for the aeronautical industry. It has the potential to reduce the overall weight of aircraft, enhance performance characteristics, and have positive economic impacts. Future work will involve producing physical specimens using the new ULCC and assessing their real-world performance before introducing the product to the market.

CRediT authorship contribution statement

Nicholas Fantuzzi: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Antoine Dib:** Writing – review & editing, Writing – original draft, Data curation. **Sajjad Babamohammadi:** Software, Formal analysis. **Silvio Campigli:** Visualization, Resources, Funding acquisition. **David Benedetti:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition. **Jacopo Agnelli:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jacopo Agnelli reports financial support was provided by Italian Ministry of Industry. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The TERSA Project tender “Accordi per l’innovazione, Fabbrica Intelligente” D.D. 27/11/2018 Project no. F/130088/05/X38 funded by Italian Ministry of Industry and co-funded by Horizon 2020 of EU.

References

[1] A. Mouritz, Aerospace materials: Past, present and future, in: Introduction to AerospaceMaterials, vol. 1, 2012, pp. 15–38, http://dx.doi.org/10.1533/9780857095152.15.

[2] A. Muhammad, M.R. Rahman, R. Baini, M.K. Bin Bakri, 8 - Applications of sustainable polymer composites in automobile and aerospace industry, in: M.R. Rahman (Ed.), Advances in Sustainable Polymer Composites, in: Woodhead Publishing Series in Composites Science and Engineering, Woodhead Publishing, 2021, pp. 185–207, http://dx.doi.org/10.1016/B978-0-12-820338-5.00008-4.

[3] C. Wu, F. Xu, H. Wang, H. Liu, F. Yan, C. Ma, Manufacturing technologies of polymer composites—A review, Polymers 15 (2023) 712, http://dx.doi.org/10.3390/polym15030712.

[4] C. Chawla, Composite Materials: Science and Engineering, Springer, 2019.

[5] H.B. Dexter, D. Noonan, Composite materials in aircraft structures, AIAA J. 36 (1998) 1653–1658, http://dx.doi.org/10.3390/polym15030712.

[6] Y.-L. Pan, W.-H. Liao, Z.-Y. Wu, J.-C. Jhang, F.-R. Gu, Modeling and enhancement of general dynamics F-16 fighting falcon missile launching system based on Petri nets, in: 2023 9th International Conference on Applied System Innovation, ICASI, 2023, pp. 6–8, http://dx.doi.org/10.1109/ICASI57738.2023.10179590.

[7] C. Soutis, Carbon fiber reinforced plastics in aircraft construction, Mater. Sci. Eng. A 412 (1) (2005) 171–176, http://dx.doi.org/10.1016/j.msea.2005.08.064, International Conference on Recent Advances in Composite Materials.

[8] C. Soutis, Fibre reinforced composites in aircraft construction, Prog. Aerosp. Sci. 41 (2) (2005) 143–151, http://dx.doi.org/10.1016/j.paerosci.2005.02.004.

[9] M. Mrazova, Advanced composite materials of the future in aerospace industry, Incas Bull. 5 (3) (2013) 139.

[10] Y. Li, Y. Xiao, L. Yu, K. Ji, D. Li, A review on the tooling technologies for composites manufacturing of aerospace structures: Materials, structures and processes, Composites A 154 (2022) 106762, http://dx.doi.org/10.1016/j.compositesa.2021.106762.

[11] W. Roeseler, B. Sarh, M. Kismarton, Composite structures: The first 100 years, in: 16th International Conference on Composite Materials, Society for Composite Materials, Kyoto, 2007.

[12] J. Njuguna, in: J. Njuguna (Ed.), Lightweight Composite Structures in Transport Design, Manufacturing, Analysis and Performance, Woodhead Publishing, 2016.

[13] L. Setlak, R. Kowalik, T. Lusiak, Practical use of composite materials used in military aircraft, Materials 14 (2021) http://dx.doi.org/10.3390/ma14174812.

[14] M. Skaff, F-35 lightning II cockpit vision, SAE Int. J. Passeng. Cars - Electron. Electr. Syst. 3 (2010) 131–140, http://dx.doi.org/10.4271/2010-01-2330.

[15] I. Sioutis, K. Tserpes, A literature review on crack arrest features for composite materials and composite joints with a focus on aerospace applications, Aerospace 10 (2023) 137, http://dx.doi.org/10.3390/aerospace10020137.

[16] A. Aabid, B. Parveez, N. Parveen, S. Khan, M.A. Raheman, M. Zayan, O. Shabbir, Reviews on design and development of unmanned aerial vehicle (drone) for different applications, J. Mech. Eng. Res. Develop. 45 (2022) 53–69.

[17] G. Goh, W. Toh, Y. Yap, T. Ng, W. Yeong, Additively manufactured continuous carbon fiber-reinforced thermoplastic for topology optimized unmanned aerial vehicle structures, Composites B 216 (2021) 108840, http://dx.doi.org/10.1016/j.compositesb.2021.108840.

[18] J. Zhang, G. Lin, U. Vaidya, H. Wang, Past, present and future prospective of global carbon fibre composite developments and applications, Composites B 250 (2023) 110463, http://dx.doi.org/10.1016/j.compositesb.2022.110463.

[19] V. Giurgiutiu, 16 - Structural Health Monitoring (SHM) of aerospace composites, in: P. Irving, C. Soutis (Eds.), Polymer Composites in the Aerospace Industry, Woodhead Publishing, 2015, pp. 449–507, http://dx.doi.org/10.1016/B978-0-85709-523-7.00016-5.

[20] G. Goh, S. Agarwala, G. Goh, V. Dikshit, S. Sing, W. Yeong, Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential, Aerosp. Sci. Technol. 63 (2017) 140–151, http://dx.doi.org/10.1016/j.ast.2016.12.019.

[21] Y. Wen, M. Jian, J. Huang, J. Luo, L. Qian, J. Zhang, Carbonene fibers: Toward next-generation fiber materials, Nano Lett. 22 (15) (2022) 6035–6047, http://dx.doi.org/10.1021/acs.nanolett.1c04878.

[22] C. Zhang, Y. Ling, X. Zhang, M. Liang, H. Zou, Ultra-thin carbon fiber reinforced carbon nanotubes modified epoxy composites with superior mechanical and electrical properties for the aerospace field, Composites A 163 (2022) 107197, http://dx.doi.org/10.1016/j.compositesa.2022.107197.

[23] S.G. Kim, S.J. Heo, S. Kim, J. Kim, S.O. Kim, D. Lee, S. Lee, J. Kim, N.-H. You, M. Kim, H.C. Kim, H.G. Chae, B.-C. Ku, Ultrahigh strength and modulus of polyimide-carbon nanotube based carbon and graphitic fibers with superior electrical and thermal conductivities for advanced composite applications, Composites B 247 (2022) 110342, http://dx.doi.org/10.1016/j.compositesb.2022.110342.

[24] A. Nayab-Ul-Hossain, S.K. Sela, M. Hasib, M. Alam, H.R. Shetu, Preparation of graphene based natural fiber (Jute)-synthetic fiber (glass) composite and evaluation of its multifunctional properties, Composite C 9 (2022) 100308, http://dx.doi.org/10.1016/j.jcomc.2022.100308.

[25] P. Gong, L. Hao, Y. Li, Z. Li, W. Xiong, 3D-printed carbon fiber/polyamide-based flexible honeycomb structural absorber for multifunctional broadband microwave absorption, Carbon 185 (2021) 272–281, http://dx.doi.org/10.1016/j.carbon.2021.09.014.

[26] A. Brasington, C. Sacco, J. Halbritter, R. Wehbe, R. Harik, Automated fiber placement: A review of history, current technologies, and future paths forward, Composite C 6 (2021) 100182, http://dx.doi.org/10.1016/j.jcomc.2021.100182.

[27] R.K. Phanden, P. Sharma, A. Dubey, A review on simulation in digital twin for aerospace, manufacturing and robotics, Mater. Today: Proc. 38 (2021) 174–178, http://dx.doi.org/10.1016/j.matpr.2020.06.446, 2nd International Conference on Future Learning Aspects of Mechanical Engineering.

[28] W. Jarrett, S. Jeffs, F. Korkees, M. Rawson, The opportunities and challenges of hybrid composite driveshafts and their couplings in the aerospace industry: A review, Compos. Struct. 320 (2023) 117203, http://dx.doi.org/10.1016/j.compstruct.2023.117203.

[29] Y. Wang, J. Ge, S. Miao, T. Jiang, X. Shen, Application of hybrid artificial bee colony algorithm based on load balancing in aerospace composite material manufacturing, Expert Syst. Appl. 215 (2023) 119375, http://dx.doi.org/10.1016/j.eswa.2022.119375.

[30] Q. Guo, W. Yao, W. Li, N. Gupta, Constitutive models for the structural analysis of composite materials for the finite element analysis: A review of recent practices, Compos. Struct. 260 (2021) 113267, http://dx.doi.org/10.1016/j.compstruct.2020.113267.

[31] J.A. Palacios, R. Ganesan, Reliability evaluation based on modal parameters of carbon-nanotube-reinforced-polymer-composite material using multiscale finite element model, Physica E 125 (2021) 114318, http://dx.doi.org/10.1016/j.physe.2020.114318.

[32] A. Allahdadian, M. Mashayekhi, Experimental and numerical study of tensile behavior of carbon nanotube reinforced glass-epoxy composite: The multiscale approach, Compos. Struct. 304 (2023) 116394, http://dx.doi.org/10.1016/j.compstruct.2022.116394.

[33] Y.D. Yasuda, F.A. Cappabianco, L.E.G. Martins, J.A. Gripp, Aircraft visual inspection: A systematic literature review, Comput. Ind. 141 (2022) 103695, http://dx.doi.org/10.1016/j.compind.2022.103695.

[34] N. Fantuzzi, M. Bacciocchi, D. Benedetti, J. Agnelli, The use of sustainable composites for the manufacturing of electric cars, Compos. C 4 (2021) 100096, http://dx.doi.org/10.1016/j.jcomc.2020.100096.

[35] L. González-deSantos, J. Martínez-Sánchez, H. González-Jorge, F. Navarro-Medina, P. Arias, UAV payload with collision mitigation for contact inspection, Autom. Constr. 115 (2020) 103200, http://dx.doi.org/10.1016/j.autcon.2020.103200.

[36] B.A. Newcomb, Processing, structure, and properties of carbon fibers, Composites A 91 (2016) 262–282.