

BENEFITS AND CHALLENGES IN DESIGN, OPTIMIZATION, AND RECYCLING OF COMPOSITE MATERIALS USED IN THE AEROSPACE INDUSTRY

Abstract: This article explores the application of composite materials in the aerospace industry, emphasizing their advantages, including reduced weight, enhanced durability, and better aerodynamic performance. While these materials are crucial for improving fuel efficiency and aircraft performance, they present challenges such as high costs, repair difficulties, and recycling issues. Proposed solutions involve automating manufacturing, developing more affordable materials, refining recycling methods, and introducing new designs for specific components.

Key words: Composite materials, aerospace industry, repairability, recycling technologies, durability.

1. INTRODUCTION

Composite materials have been studied and used more frequently in recent years due to their properties and qualities (including studies on classic composites, the implementation of smart composites, etc.). Thus, the aerospace industry has shown increased interest in developing and implementing composite materials in as many structures/components as possible in aircraft, helicopters, drones, etc.

2. COMPOSITE MATERIALS

2.1 Definition of Composite Materials

Composite materials are materials made from two or more distinct components, which retain their individual characteristics but are combined to offer superior properties compared to those the components had individually. These materials are often composed of a continuous phase, called the matrix, and a discontinuous phase, called the reinforcement. The matrix is the material that surrounds and supports the reinforcing phase, ensuring cohesion between particles, while the reinforcing phase, represented by reinforcement (usually fibers or particles), imparts enhanced mechanical and thermal properties to the material [1].

2.2 Composite materials used in the aerospace industry

Composite materials are increasingly used in the manufacture of various aerospace parts/components/structures due to their reduced weight, but especially for their strength and elasticity. Composite materials allow the creation of a (customized) material that incorporates the characteristics and properties required for the specific structure, which is very important and useful when it comes to structural components in an aircraft. In Figure 1, I represented the structural components of the composite materials, which are most commonly used in aerospace structures:

- Matrix (continuous phase): metallic (aluminum, magnesium, titanium alloys), epoxy resins, polyester resins, etc.
- Reinforcement (discontinuous phase): fibers such as glass, carbon (graphite), steel, alumina, etc.

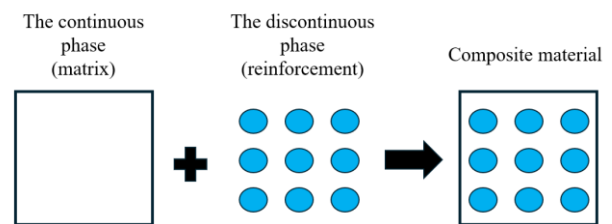


Figure 1 Composite material

To date, the proportion of composite materials in the structure of an aircraft has been up to 50%, as some structures are still difficult to manufacture from composite materials (for example, in more complex shapes, resin buildup can not be controlled, leading to differences in the structural properties of the parts). Additionally, there are areas where fiber overlap occurs when choosing for the creation of a more complex shape by joining/gluing two components, which again leads to structural differences in that area.

An example of an aircraft that used a significant proportion of composite materials in its composition is the Boeing 787 Dreamliner and Figure 2 best shows the proportion of materials used. Thus, it is observed that in this aircraft model, the Boeing 787 Dreamliner, the following materials are present: composite materials in a proportion of 50%, mainly used for the aircraft's skin, aluminum in a proportion of 20%, titanium in a proportion of 15%, steel in a proportion of 10% and other materials in a proportion of 5% [2].

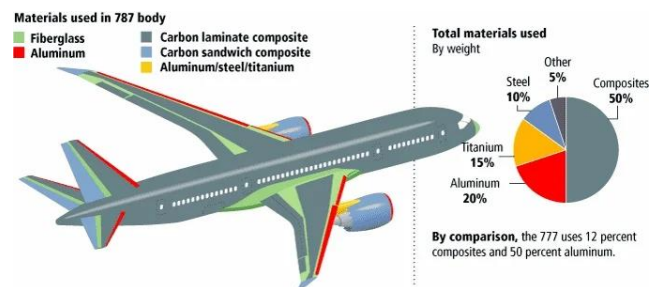


Figure 2 The materials of the Boeing 787 aircraft [2]

If we were to compare the percentage of composite materials used in the Boeing 787 Dreamliner, which is 50%, with the percentage of composite materials in the Boeing 777, which is 12%, we would see an extremely significant increase in the use of these materials.

Another example would be the Airbus A350, which has a proportion of composite materials slightly exceeding 50%, as shown in Figure 3. Thus, the proportion of materials used in the construction of the Airbus A350 is as follows: composite materials in a proportion of 54%, mainly used for the aircraft's skin, aluminum in a proportion of 19%, titanium in a proportion of 14%, steel in a proportion of 6% and other materials in a proportion of 7% [3].

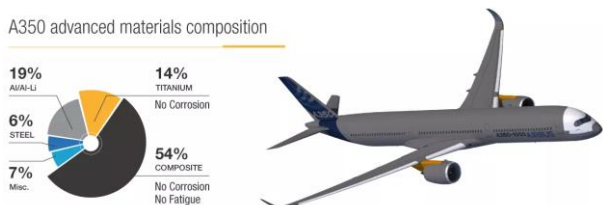


Figure 3 The materials of the Airbus A350 aircraft [3]

If we compare the two aircraft (Airbus A350 and Boeing 787), we can observe in the following table that the proportions of materials used are quite similar, with small differences.

Table 1
The proportions of materials used in Boeing 787 Dreamliner and Airbus A350 aircraft [2] [3]

Material type	Material proportion	
	Boeing 787 Dreamliner	Airbus A350
Composite materials	50%	54%
Aluminum	20%	19%
Titanium	15%	14%
Steel	10%	6%
Other materials	5%	7%

Thus, the main advantages of using composite materials in both aircraft are related to fuel consumption reduction and increased durability and reliability.

Reducing weight, a critical factor for fuel consumption, allows the Airbus A350 to consume approximately 25% less fuel than traditional aircraft, having a significant impact on reducing operating costs and CO2 emissions [4].

Similar to the Airbus A350, the Boeing 787 has about 20-25% lower fuel consumption compared to older aircraft of the same size. Composites reduce the overall weight of the aircraft and allow for a significant improvement in aerodynamic performance [5].

Composites are extremely resistant to material fatigue, meaning the aircraft requires fewer inspections and less frequent maintenance than metal-built aircraft. These

properties significantly extend aircraft service life while lowering maintenance cost.

2.3 Examples of structures made from composite materials in the aerospace domain

Composite materials are widely used in the aerospace industry due to their excellent properties of strength, lightweight, and durability.

When it comes to aircraft construction, the most important initial calculation is determining an estimated weight that ensures an optimized center of gravity, allowing the aircraft to achieve the best possible performance. Therefore, composite materials have gained significant interest in this industry, not only because of the reduced weight of the resulting parts but also because of the ability to optimize the characteristics of these materials based on the composition and proportion of the components used in their manufacturing.

The following are some examples of aircraft components made from composite materials.

The fuselage of modern aircraft, such as the Boeing 787 Dreamliner and the Airbus A350, is largely made of composite materials. These materials help reduce the weight of the aircraft, which improves fuel efficiency and reduces carbon emissions.

Additionally, the wings of modern aircraft are often made from a combination of carbon fibers and thermoplastic polymers. These are used to improve the weight-to-strength ratio, offering a lighter and more durable structure.

Figure 4 shows a portion of the Boeing 787 fuselage made from composite materials.



Figure 4 Forward fuselage of the Boeing 787 [6]

In addition, composite materials are also used in certain components of helicopters. For example, the rotor blades of some helicopters are often made from composite materials, such as carbon fibers, to provide high resistance to stress and reduce the overall weight of the rotor.

Some components of engine mounts or engine attachment structures can be made from composite materials, especially in modern aircraft.

These help reduce weight without compromising structural performance, as can be seen in Figure 5.

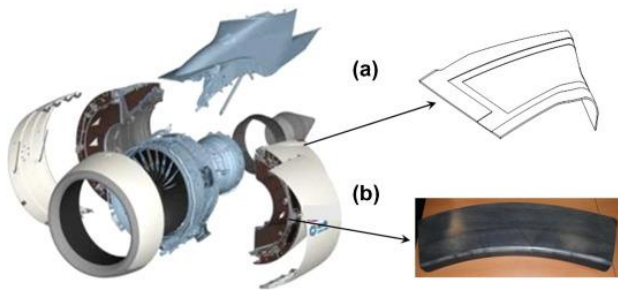


Figure 5 The composites for engine components [7]

Various parts of the landing gear, such as certain linkage components and housings, can be made from composite materials to reduce weight and improve strength performance.

Thermal protection for aircraft (including spacecraft) can be made from composite materials that include carbon fibers and other materials resistant to extremely high temperatures. These are used to protect the aircraft from the heat generated during atmospheric re-entry. Interior components, such as wall panels, ceilings, and furniture elements, can be made from fiberglass-based composites. These offer a good combination of strength and low weight, which is essential for fuel efficiency. Of course, flaps and ailerons, which are essential components for aircraft control, also use composite materials in their construction, helping to reduce weight and improve aerodynamic performance.

Doors and other hardware components of aircraft (e.g., access doors or baggage compartments) can be built from composite materials, helping to maintain low weight and improve safety.

In some cases, the hardware and window frames of the cockpit or other fuselage hardware are made from composite materials to provide a balance between low weight and structural safety.

These examples illustrate how composite materials are widely used in aircraft to reduce weight, improve aerodynamic performance, and enhance the durability of components, thereby contributing to the overall efficiency of the aircraft.

Long and continuous fiber-reinforced composites have traditionally been dominated by thermosetting polymer matrices. These thermosetting materials are particularly well-suited for impregnation into the reinforcing fibers through manual or semi-automated techniques. As a result, thermosetting (TS) matrix composites have been widely spread in aeronautical applications for the past four decades. However, TS-based composites face several challenges during manufacturing, such as the need for low-temperature storage, long curing times, and irreversible processes. Today, high-performance thermoplastic matrix composites (e.g., PEEK = Polyetheretherketone is a high-performance engineering plastic that is frequently used in composite materials and PPS = Polyphenylene sulfide is a semi crystalline, thermoplastic high temperature polymer and chemically known as polyphenylene sulphide) are emerging as promising alternatives to overcome these limitations. Crystallinity in high-

performance polymers is vital, as it significantly affects both chemical and mechanical properties. The crystalline phase enhances stiffness and tensile strength, while the amorphous phase is more effective at absorbing impact energy [8].

3. ADVANTAGES AND DISADVANTAGES

In general, the use of composite materials in the aerospace industry provides significant benefits in terms of performance and efficiency, but also involves challenges related to cost, reparability, and sustainability. Therefore, the main advantages and disadvantages of composite materials used in aerospace engineering will be briefly outlined below.

The main advantages are as follows:

Reduced weight: composite materials, such as carbon fiber or fiberglass, are much lighter than traditional materials like aluminum.

This results in a significant reduction in the weight of aircraft structures, contributing to greater fuel efficiency and improved performance.

Strength and durability: composite materials offer excellent mechanical strength and high durability, being far more resistant to corrosion compared to metals.

This makes aircraft more durable and requires less long-term maintenance.

Higher resistance to fatigue: composites are more resistant to damage caused by material fatigue, an important factor in the aerospace industry, where aircraft undergo repeated loading cycles and takeoffs.

Design flexibility: composite materials allow for complex and customized designs, as they can be produced in various shapes and are easy to mold. This means that engineers can create aerodynamically more efficient structures and optimize aircraft performance.

Thermal and acoustic insulation: composites can provide better thermal and acoustic insulation compared to traditional materials, leading to a more comfortable flying environment and protecting sensitive components from extreme temperatures [9].

There are also some disadvantages, such as:

High production costs: the manufacturing process of composite materials is often more expensive than using traditional materials.

The advanced technology required for their production and handling can lead to higher initial costs.

Difficulties in repair: composites are more difficult to repair compared to traditional materials, and superficial damage can affect the structural integrity more significantly.

Repairing them requires specialized techniques and state-of-the-art equipment, which can complicate the process.

Recycling impact: composite materials are more difficult to recycle than traditional materials, which can raise issues regarding long-term sustainability, especially at the end of an aircraft's life cycle.

Unpredictable behavior under extreme stress: under certain extreme conditions, such as impacts, composite materials can exhibit unpredictable behavior (e.g., sudden cracking) or may be vulnerable to damage from delamination.

Anisotropic properties: composites have anisotropic properties, meaning their mechanical characteristics vary depending on the direction of the fibers. This can require more careful design and detailed evaluation of the structural behavior [9].

For example, an I-shaped spar is difficult to be manufactured from composite materials due to the fiber distribution, resulting in resin accumulation at the top and bottom (as I represented in Figure 6), which is undesirable because it affects the strength of the structure under various loads.

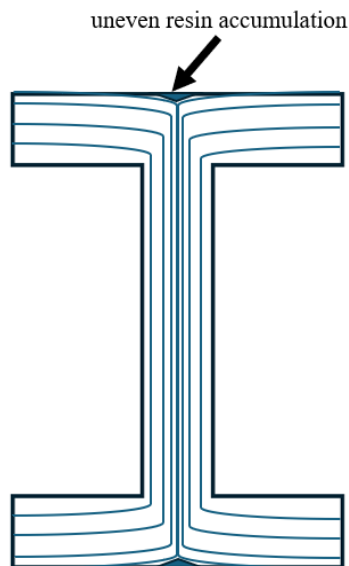


Figure 6 Wing spar I

Thus, although composite materials bring significant benefits to the aerospace domain, their successful integration depends on addressing challenges related to the manufacturing process, repairs, and sustainability [9].

4. SOLUTIONS TO OVERCOME THE DISADVANTAGES

To overcome the disadvantages associated with composite materials in the aerospace industry, various technological solutions and development strategies can be implemented.

High production costs can be addressed by automating manufacturing processes through the implementation of automated production technologies such as additive manufacturing or automated machining.

This significantly reduces production costs by improving efficiency and reducing work times.

Additionally, the development of new, more affordable composite materials is foreseen in numerous studies for the development of cheaper composite materials, such as natural fibers or recyclable materials, which could reduce production costs.

As the volume of composite production increases, manufacturing costs will decrease due to economies of scale.

Repair difficulties can be addressed by implementing advanced repair technologies. In recent years,

investments in modern repair technologies, such as the use of composite repair materials (such as carbon fiber repair kits) or automated inspection and repair procedures, have improved the restoration process for damaged components.

Research on self-healing materials has been increasingly moved forward in recent times. Thus, the development of composite materials that can "self-repair" small cracks or damages by integrating special additives which activates in the event of an impact could contribute to solving this issue.

Innovative recycling technologies, through the development of more efficient methods for recycling composite materials, such as chemical or mechanical processes for breaking down fibers and recovering resources, can significantly reduce the environmental impact.

The design of composites based on more easily recyclable materials, such as bioplastics or thermoplastic polymers, can contribute to better sustainability of these materials.

Unpredictable behavior under extreme stress could be addressed by improving simulations and testing. The use of advanced computer simulation methods and more rigorous testing (e.g., stress and fatigue behavior simulations) can help anticipate and prevent unpredictable behaviors of composite materials.

Additionally, the integration of sensors into structures for continuous monitoring of the material's condition, capable of detecting microcracks or damage before they become critical, can help prevent accidents and further damage.

Anisotropic properties (which vary depending on the fiber direction) could be resolved by adopting an optimized design for fiber orientation. By carefully designing the composite structure so that fibers are aligned according to the specific stresses of the components, performance can be maximized and risks associated with material anisotropy can be minimized.

Furthermore, research and development of polymer matrices that minimize the effects of anisotropy could help produce composite materials with more uniform properties [10].

5. RECYCLING OF COMPOSITE MATERIALS

Due to the way composite materials are produced, recycling them by separating the two phases to allow the reuse of fibers in their intact form is quite complicated to achieve, and sometimes even impossible.

Despite the challenges in recycling composite materials, recent research and technological advancements are offering solutions for the efficient recycling of composites used in the aerospace industry. Some essential aspects of composite material recycling in this field are presented below.

The complex structure of these materials makes them difficult to separate, as composites used in the aerospace industry are often made from a combination of fibers (such as carbon, glass, Kevlar, basalt fibers, and boron fibers etc.) and a polymer matrix (typically a thermosetting resin: epoxy, phenolic, or polyester).

The thermal and chemical resistance of these materials makes them hard to recycle, as many composites used in the aerospace industry have a thermoset matrix that cannot be easily melted and reused, unlike thermoplastic materials that can be reprocessed.

It is also worth mentioning that recycling technologies are often costly and are not yet widely adopted in the industry due to high prices and the laborious processes required for separating and processing the materials.

5.1 Recycling Methods for Composite Materials Used in the Aerospace Industry

Mechanical Recycling: this involves shredding and grinding composite materials to create pellets that can be used for manufacturing new products. It is a simple method but not suitable for all types of composites, especially those containing short fibers or that degrade the mechanical properties of the material.

Thermochemical Recycling: pyrolysis involves decomposing composite materials by heating them in an oxygen-free environment (to prevent combustion). Carbon or glass fibers can be recovered and reused, while the polymer matrices decompose into a more manageable form. It is a promising technology, but its high costs and its precise process control remain significantly challenging [11].

Solvent Recycling: in this method, composite materials are treated with solvents to dissolve the polymer matrices, thus separating them from the carbon or glass fibers. This is an efficient process for some types of composites, but solvents can be hazardous and costly.

Reheating Recycling (Thermoplastic Recycling): thermoplastic-based composite materials are easier to recycle because they can be melted and reprocessed into new shapes. Therefore, thermoplastic composites can be reused in the production of new components, including for aerospace applications [11].

5.2 Examples of Possible Applications of Recycled Composite Materials

In the aerospace industry, major companies (such as Boeing and Airbus) collaborate with universities and research institutes to develop more efficient and cost-effective solutions for recycling composite materials. Some aerospace companies are exploring the reuse of damaged composite parts and components by refurbishing them instead of completely recycling them. Additionally, recycling composite materials reduces the amount of waste generated by the aerospace industry and contributes to the reduction of CO₂ emissions associated with the production of new materials [12].

Furthermore, although the recycling process is initially more expensive, in the long term, it can lead to significant savings in materials and resources.

By implementing efficient recycling processes, the aerospace industry can become more sustainable, considering the increasingly strict regulatory requirements regarding environmental protection.

Currently, research is ongoing to find more economical and faster methods of recycling composite materials, including improving fiber separation and recovery technologies.

The industry must overcome economical and logistical barriers to widely adopt efficient recycling solutions that can be implemented in existing supply chains [13].

Thus, recycled composite materials can be used in other industries, such as the automotive industry, as shown in Figure 7.

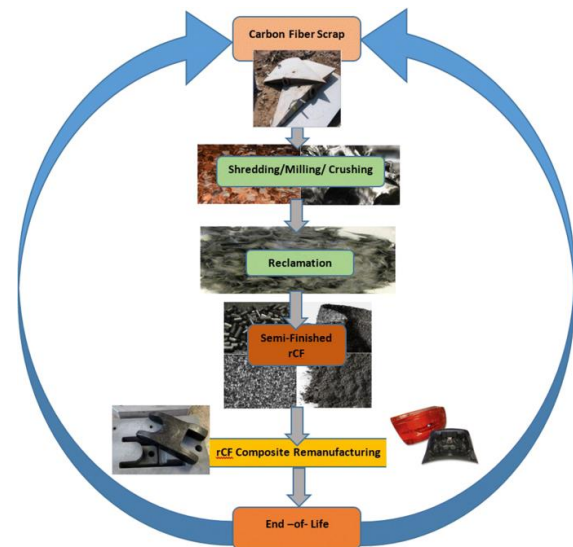


Figure 7 Recycled Carbon Fibers (rCF) in Automobiles [14]

Recycled composite materials can also be used for manufacturing various components inside the aircraft, such as passenger seats, tray tables, small components, etc.

One example of using recycled composite materials could be the production of a tray table, as shown in Figure 8. This tray table features a new design, being much more passenger-friendly through the implementation of rounded shapes and the presence of circular arches integrated into the surface of the table. This tray table meets the needs of passengers by providing space for storing cutlery, two special spaces for glasses, a holder for devices like tablets or mobile phones, and the possibility to be used in either an extended or compact version, etc.

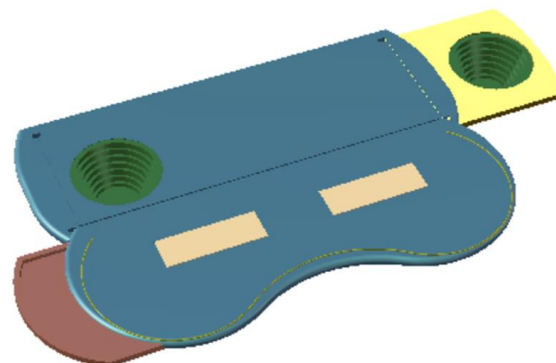


Figure 8 The configuration of the tray table [15]

6. CONCLUSIONS

In conclusion:

- The use of composite materials brings considerable advantages, such as reduced

weight, high durability, increased fatigue resistance, and design flexibility. However, there are also disadvantages, such as high production costs, difficulties in repair, impact on recyclability, and unpredictable behavior under extreme stress.

- To overcome the disadvantages of composite materials, solutions such as automating manufacturing processes, developing new, more affordable materials, and researching self-healing materials are recommended. Additionally, innovative recycling technologies and improving simulations and testing can help address issues related to recyclability and unpredictable behaviors.
- Recycling composites is challenging due to their complex structure and the difficulty of separating fibers from the matrix. However, emerging technologies, such as mechanical, thermochemical, and solvent-based recycling, are making strides toward more efficient recycling processes. Additionally, the aerospace industry is exploring ways to reuse damaged composite parts and reduce waste generation.

7. FURTHER DEVELOPMENTS

The following possible developments will be considered:

- Studying and creating a new type of fabric
- Creating test samples
- Analyzing the samples and their properties
- Redesigning certain components of an aircraft

REFERENCES

- [1] Andrew C. Marshall, *Composite Basics*, Sixth Edition, first printing August 2001, published by Marshall Consulting, printed in the United States of America, total number of pages 195.
- [2] Research Gate. (n.d.). *Composite structure of Boeing 787*. Available at: https://www.researchgate.net/figure/Composite-structure-of-Boeing-787_fig3_317607272, Accessed: 2025-03-29.
- [3] Airbus Aircraft. (n.d.). *Less fuel burn and maintenance. More savings*. Available at: <https://aircraft.airbus.com/en/newsroom/case-study/2023-01-a350-less-operating-cost-more-capabilities>, Accessed: 2025-03-29.
- [4] Airbus. (n.d.). *A350 Family. The Long Range Leader*. Available at: <https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft/a350-family>, Accessed: 2025-03-29.
- [5] Boeing. (n.d.). *787 Dreamliner structural testing program*. Available at: <https://www.boeing.com/commercial/787/quality-info#structural-testing>, Accessed: 2025-03-29.
- [6] Kawasaki. Powering your potential. (n.d.). *Reducing Airframe Weight. Composite material used in the Boeing 787*. Available at: <https://global.kawasaki.com/en/corp/rd/technologies/air2.html>, Accessed: 2025-03-29.
- [7] Science Direct. Elsevier. (n.d.). *About the influence of stamping on thermoplastic-based composites for aeronautical applications*. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S135983681200501X>, Accessed: 2025-03-29.
- [8] B. Vieille, W. Albouy, L. Chevalier, L. Taleb (2013) *About the influence of stamping on thermoplastic-based composites for aeronautical applications*. Composites Part B: Engineering, Volume 45, Issue 1, February 2013, Pages 821-834
- [9] L. Taleb, S. B. Park, F. L. Matthews, H. M. Wang, A. M. A. Ameen (2011) *Advantages and challenges of composite materials in aerospace applications*. Composites Part A: Applied Science and Manufacturing, Volume 42, Issue 10, October 2011, Pages 1390-1399
- [10] J. L. Joffe, A. M. B. L. Lambourne, C. D. R. Paxton (2015) *Advances in the repair of composite materials for aerospace applications*. Composites Part B: Engineering, Volume 78, July 2015, Pages 1-14.
- [11] J. S. P. R. de Almeida, D. C. A. P. Lima, M. F. M. Vieira, L. C. T. Santos, R. A. Ribeiro (2020) *Recycling of composite materials: A review of methods and applications*. Journal of Cleaner Production, Volume 276, Article 123178, July 2020.
- [12] J. S. P. R. de Almeida, M. F. M. Vieira, D. C. A. P. Lima (2019) *Advances in recycling of composite materials: An aerospace industry perspective*. Procedia CIRP, Volume 83, 2019, Pages 675-680.
- [13] B. Vieille, W. Albouy, L. Chevalier, L. Taleb (2013) *About the influence of stamping on thermoplastic-based composites for aeronautical applications*. Composites Part B: Engineering, Volume 45, Issue 1, February 2013, Pages 821-834.
- [14] Research Gate. (n.d.). *Recycling loop of carbon fibers from landfills/other scraps*. Available at: https://www.researchgate.net/figure/Recycling-loop-of-carbon-fibers-from-landfills-other-scraps_fig1_342871241, Accessed: 2025-03-30.
- [15] Paula-Mălina Ichim (Vieriu), dissertation supervisor Conf. Ph.D., Eng. Victor Gabriel Adir, *Design of meal tables placed on the backrests of seats in an airplane cabin*. National University for Science and Technology Politehnica Bucharest, Faculty of Aerospace Engineering, Engineering Graphics and Design, July 2024.

Author(s):

Eng. Paula-Mălina VIERIU, National University for Science and Technology Politehnica Bucharest, Doctoral School of Industrial Engineering and Robotics, E-mail: paulamalina15@gmail.com

Prof. Ionel SIMION, National University of Science and Technology Politehnica Bucharest, Doctoral School of Industrial Engineering and Robotics, E-mail: ionel.simion@upb.ro