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Carbon Composites in Aerospace Application - A Comprehensive Review

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Abstract: There has been a huge change in the aerospace industry due to using carbon composites as a primary manufacturing component. The aerospace industry is now using more than 50% carbon composites as a primary design product in aircraft. The weight of the aircraft and its fuel consumption can be minimized by using carbon fiber composites in the design of the aircraft. Affordability is a very important aspect of the aerospace industry; using carbon composites makes manufacturing civil, cargo, and military aircraft easier, with the help of carbon fiber, making the aircraft more lightweight. The aerospace industry recently launched two aircraft, Boeing 787 Dreamliner and Airbus A350 XWB, in which more than 50 to 53% carbon fiber is used as a primary design product. By using carbon fiber, the improvement in the overall efficiency of an aircraft is observed. This paper aims to review the applications of carbon fiber and find carbon composites are effective in the applications of the aerospace industry.

Keywords: composite; aerospace; carbon fiber composites; composite manufacturing; mechanical test.

1. Introduction

In recent times composites have been the most demandable material in various sectors such as automobile, aerospace, sports, construction, medical, etc. Various composites like glass, carbon, and Kevlar fibers have been frequently designed and fabricated for aircraft parts. Carbon fiber composites are largely used in the aerospace industry due to their excellent performance features [1]. Carbon composites are very demandable in the aerospace industry due to their properties, such as high strength, low fuel consumption, weight reduction, corrosion resistance, high stiffness, high modulus, etc. Carbon composite improves the properties of metal alloys, which makes them able to satisfy all extreme conditions. In the aerospace industry, the most important property of carbon composite is fatigue fracture resistance; this property helps the aircraft during take-off and landing time. By replacing conventional metal alloys with carbon composites in aircraft design, the weight of an aircraft is reduced, which is essential; as a result of the weight reduction, fuel consumption is reduced, and thus cost is reduced. Recently, in the aerospace industry, the Boeing 787 Dreamliner has been manufactured with more than 50% of carbon composites in terms of volume by nearly about 80% [2,3].

The main concentration in this paper has been given to the carbon composite applications in the aerospace industry and the uses of carbon composites in manufacturing aircraft parts.

2. Materials and Methods

2.1. Composite materials are classified as follows.

2.1.1. Metal Matrix Composites(MMC).

These are made from a metal matrix, including predominantly aluminum, cobalt, magnesium, iron, copper, and titanium, as well as a distributed ceramic or phase reinforcing phase [3-5]. Matrix materials are chosen depending on the application's required qualities and service circumstances. The quantity of reinforcement employed in the composite might be up to 50% of the total volume. SiC particles, Boron and Al_2O_3, and Borsic and TiB_2-coated carbon may mix quickly and effectively. Due to their amazing strength at high temperatures and great corrosion resistance, aluminum and titanium are the two most often used metal matrices in the automotive and aerospace industries [6-8].

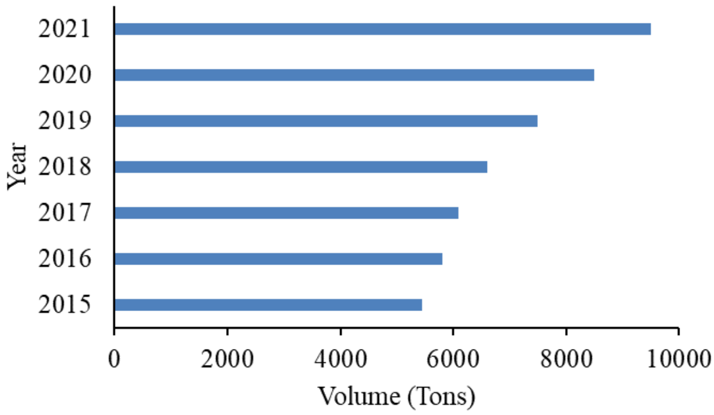

Figure 1. Global demand for Metal Matrix Composites.

From figure 1, it is realized that the demand for metal matrix composites is growing continuously. According to 'markets and market' report, the global composite metal is expected to increase from USD 467 million in 2020 to USD 787 million in 2025. The use of metal matrix composites in the automotive and transportation industries, as well as in aerospace, is driving growth in the metal matrix composite market. Weight reduction of aircraft is the most important factor, as well as the strength-to-weight ratio, which is also an important factor in aviation and aeronautics [2].

2.1.2. Ceramic Matrix Composites(CMC).

A ceramic matrix reinforced with a ceramic matrix such as aluminum oxide, carbon, and silicon nitride makes up these. Ceramics are used in aerospace applications because they have several desirable properties, including strong toughness and stability at high temperatures, as well as wear resistance. Both short and long fibers can be employed to achieve a specific level of quality. The toughness of the short-Ceramic Matrix Composite makes it more resistant to fracture propagation, but it also has a catastrophic failure mode. The scattering phase in continuous monofilaments provides the highest strengthening effect[9-11].

2.1.3. Reinforcement phase.

Carbon, glass, metal, and Kevlar are inserted into the matrix as reinforcement. These are generally hard and provide high strength, stiffness, temperature resistance, and wear resistance. Reinforcements come in the form of particles, sheets, and whiskers. Their primary purpose is to carry the load imparted to the composite. Glass is now widely employed in manufacturing automobile parts, boat hulls, sports gear, and architectural ornamental panels. Recent research has revealed that silicon carbide particles, boron nitride, aluminum oxides, and zinc oxide are the optimum reinforcing materials for polymer matrix to accomplish certain mechanical and electrical characteristics [11,12].

3. Composite Materials used in Aerospace

Several types of composite materials are available, but carbon fiber reinforced for aerospace structural applications is popular due to its certain properties like high tensile strength, high modulus, low cost, low creep, etc. [13-15]. In aviation, carbon fiber has been used almost everywhere. According to reports, the Boeing 787 Dreamliner passenger airliner is made up of 50% composite material by weight, with carbon fiber laminate or carbon fiber sandwich accounting for most of the composite material. Carbon fiber is used in various parts, including the fuselage, horizontal and vertical wings, tail, doors, and interior parts. The details of carbon composite used in aviation are shown in Figure 2. In addition to fuel efficiency, Boeing points out that carbon and other composite materials require less maintenance because they do not corrode or fatigue like metals. Carbon fiber planes are more profitable since they require less maintenance and have more flight duration.

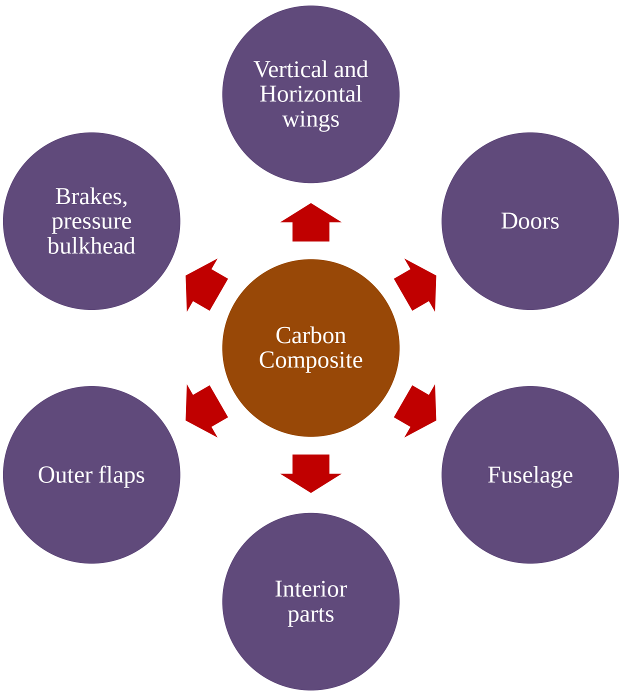

Figure 2. Application of carbon composite.

Composite materials have two modes of fabrication: the film stacking method and the manufactured method; it is classified into various categories due to their mechanical, physical, and chemical characteristics [16,17]. For aircraft design, although carbon composites are used, the selected must have specific physical-mechanical and chemical properties that suit the manufacturing because by using these properties materials, we improve the overall efficiency of aircraft, reducing the weight, etc. In Boeing, the most important parameters are weight and fuel reduction by using carbon composites effectively. We can improve fuel efficiency by up to 10%–12%, and we can also improve weight saving by up to 20% [3]. Carbon fiber composites have applications for the exterior and interior of aircraft. For example, in cabins, seats, cargo doors, etc. The material selection is made by checking/evaluating the performance of carbon composite against the different criteria specified in material standards. This selection process is very difficult and complex due to many suggestions; therefore, this decision-making process is called Multi-Criteria Decision-Making process (MCDM). The reported composites materials are found to maintain their properties, especially physical properties, at high temperatures and can stay for a long period in thermal stability [18,19]

3.1. Boeing 787-Dreamliner.

The Boeing 787 Dreamliner is a long-range commercial aircraft that extensively uses carbon composites as a key production material. It is the world's first passenger aircraft capable of covering a great distance with minimal fuel. Carbon composites are employed in different elements of the Boeing 787 Dreamliner, including the wings, wings bars, fuselage section, tail, and so on. The usage of carbon fiber improves an aircraft's overall efficiency while also making it more lightweight. Because of its low fuel usage, it can transport more passengers in less time [16-20]. Following the adoption of carbon fiber composites in the Boeing 787 Dreamliner, other airlines, such as Beech Starship, began incorporating carbon composites in their aircraft designs. This is a US business aircraft, and the quantity of carbon fiber utilized in the wings and fuselage structure is around 90%. More than 15% of carbon composites were utilized in the production process of the Airbus A320-340, for example [20].

3.2. Airbus A350-XWB.

Following Boeing's lead, Airbus began employing carbon-fibered composites in its airplane production designs. With a broad range and increased white body build-up, the Airbus A350 XWB is the second most aircraft that employs more than 50% carbon composites in its manufacturing design. In December 2014, Qatar Airlines received the first Airbus A350 XWB aircraft. In January 2015, Qatar Airlines became the first airline to fly the Airbus A350 XWB [5-7]. The Airbus A320-340 is a European commercial aircraft. This airplane is constructed using 15% composite throughout the production process. Empennage [20,21] is the structure they created using carbon composite.

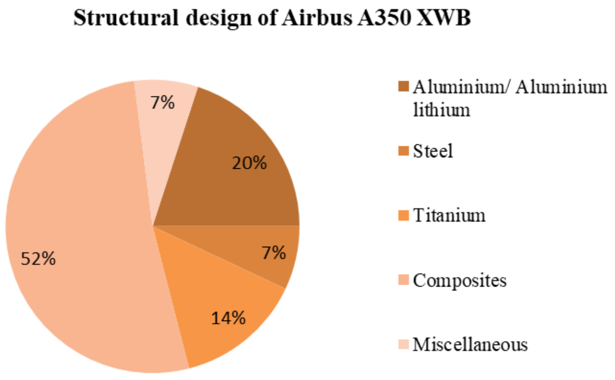

Figure 3. Structural Design of Airbus A350 XWB.

Carbon composites have recently gained prominence in the design of commercial aircraft, such as the Airbus A350-XWB and Boeing 787 Dreamliner, as well as military aircraft. Composites are used in 53 percent of the Airbus A350-XWB (Figure 3) and 50 percent of the Boeing 787 Dreamliner. The aircraft design with qualities such as low fracture toughness, low thermal shock absorber, and high tensile strength is done with a carbon fiber-reinforced polymer matrix [21].

3.3. Airbus A400M.

The Airbus A400M industry also utilized carbon composites in its design process. The Airbus A400M industry's motivation for using carbon composites in the design process is to lower total weight by up to 30%. Carbon composites are employed in several elements of the Airbus A400M, including the tail section, which houses the aircraft's control surfaces. When carbon composites are used in aviation design, the aircraft becomes lighter and performs better[22,23].

3.4. Airbus A380.

Carbon composites are also used in the design of the Airbus A380. Initially, aluminum was the primary metal used in aircraft design. Still, because it is a heavy metal that does not maintain a good balance with external environments such as humidity and rain, the aviation industry shifted to carbon composites, which made aircraft lighter. Carbon composites are employed in various Airbus components, including the rear pressure bulkhead, central wings box, tail cone, and wing flaps. Carbon composites are used in the design process because they provide precise stiffness, a high strength-to-weight ratio, and low yield strength and low stiffness [22-24].

4. Composite Manufacturing

There are different manufacturing processes used for composite manufacturing. Compression molding, filament winding, and resin transfer molding are some of the processes used for aerospace composite. Adding two or more reinforced polymers in a single one results in the formation of hybrid composites and has attracted many researchers to work on it [2]. Open molding and closed molding are the two methods for producing any carbon composite for aviation. In molding and finishing procedures, composite fibers are instantly drained from the resin solution.

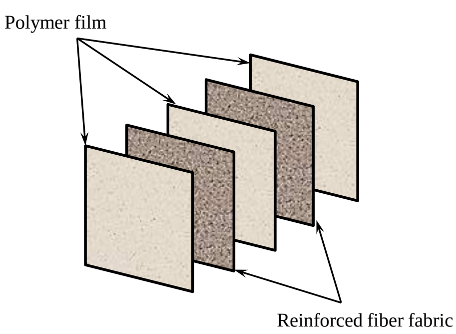

Figure 4. Layer-by-layer arrangement of thermoplastic film and reinforced fiber by film stacking method.

Composites are created by combining three different materials. In the presence of natural rubber particles, epoxy resin, catalyst hardener, and natural rubber particles are mixed. The liquid is then poured into the die, which is subsequently covered in fiber and repeated. Compression die molding is widely used in this method. Carbon fiber-reinforced polymers are mainly produced by the process of compression molding in a hydraulic compression press [1]. The composite material preparation starts layer-by-layer, and then reinforced fiber fabric and the polymer film is placed one by another. This method is known as the film stacking method [1], as given in Figure 4.

After pressing the mixture into a die and curing it for two days, the required CFRP manufacturing item was required. The components used in the manufacturing process include epoxy resin, natural rubber, carbon fibers, and other elements. Assessing carbon composites' mechanical properties is one of the most useful components of the manufacturing process. The dependency of particle numbers on the manufacturing process is an important factor in a material's stiffness and strength [25,26]. The various composite manufacturing processes are shown in Figure 5.

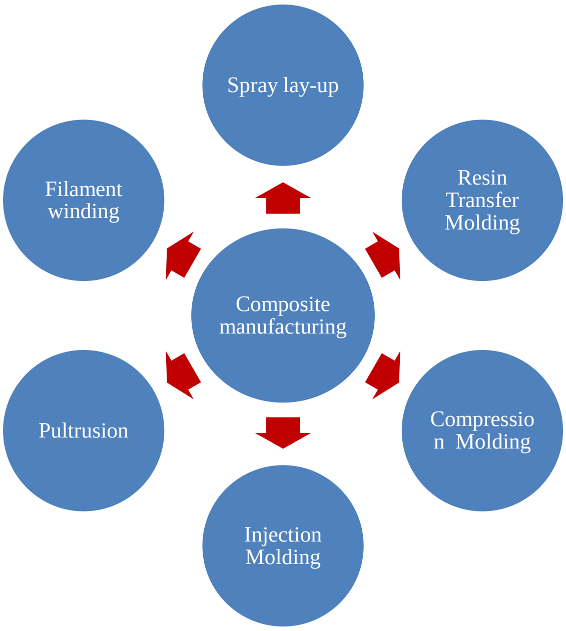

Figure 5. Composite Manufacturing.

5. Structural Health Monitoring (SHM)

Following aircraft production, it must ensure that all components are working correctly and that any parts that require repair have been detected using sensor data. Sensors are extremely important in the functioning of aeroplanes. The SHM Sensor is a device that monitors the aircraft's overall health [13,14]. The complete health monitoring system is made up of sensors, as well as data storage and gathering equipment. The SHM sensor's goal is to detect structural damage to a part unaffected by changes in the external environment. As soon as it senses the damage, it will send a signal to the host; however, it must be able to survive in the external environment for some time while the damage is healed [28,39]. The SHM sensor includes data transmission, signal processing, surface detection treatment, and other operations. SHM evaluates the overall performance of material throughout its full life cycle. Damage to aircraft structures, such as deboning at the face layer boundary, can be detected using the SHM sensor [14,15,28].

When a piece or component is damaged, it changes the structure's shape, stiffness, and strength;fiber optic sensors are used to tackle these problems. Fiber optic sensors are small, light, and have a large bandwidth. Fiber optic sensors use techniques including wavelength, polarization phase, and intensity measurement to detect structures' damage, and these sensors discover defects in structures by detecting less velocity damage. All things are examined for signs of tension and strain. This is a very inexpensive fiber that can be employed easily. Optical fiber sensors in large aircraft areas when SHM sensors aren't possible. In every sort of composite matrix, fiber optics are used. This fiber optic is exceedingly expensive and sensitive to temperature changes. This low-cost fiber optic sensor comprises telecom optical fibers [14-15,23-25,35]. This fiber optic sensor offers wide bandwidth, is long-lasting, and is light in weight.

6. Mechanical Test and Properties of Carbon Composites

Several organizations have standardized composite examinations. ASTM, ISO, and CEN (European Committee for Standardization) are the most important worldwide composite testing standards. In addition to worldwide standards, several manufacturer-specific standards, such as Boeing's BSS series and Airbus'AITM series, are widely used. ASTM D 3039, EN 2561, EN 2597, ISO 527-4, and ISO 527-5 are popular laminate tensile testing standards. ASTM D695, ASTM D3410, ASTM D6641 are used for Compression test.

6.1. Mechanical test types.

Most mechanical testing for creating carbon composites occurs under compression, tensile, and other tests such as flexural strength and shear strength. The following are the tests widely used to obtain various properties [17,28,33].

6.1.1. Static evaluation.

The static test is used to measure the strength and strain capacity of the material. A tensile load was used to accomplish this test. The specimen's strength and strain capacity are also determined using the creep test. The average percentage range for doing these two tests at different short-term ultimate tensile strength percentages is 10-60 percent [28,33].

6.1.2. Test of cyclic loading.

When a specimen is subjected to recurrent static stresses, this test will measure how resistant it is to breaking. To reduce heating, the frequency of testing applications for composite materials is to be kept around 5-10Hz. Tension-tension, tension-compression, or spectrum loading at constant amplitude must be employed to simulate genuine loading conditions in a given application. When making laminates, the ASTM standards should be followed. These recommendations are used to choose acceptable specimens for tensile testing on a universal testing machine (UTM) to determine laminate's flexural and tensile modulus. The dial indicates all of the many ways to expand for the device to expand and engage when the specimen is split; however, if the specimen cannot split, the gadget records the point where the specimen would break and elevates the stress concentration by 3.5 percent. The impact resistance of various materials is tested using dynamic loads. The preceding tests are carried out under various loading conditions, including tensile and compressive loads, and when an impactor is present.

An impact happens in a chosen specimen under uncommon conditions during a tensile or compressive loading phase. One million seconds is the loading interval. These tests are conducted at various temperatures and amounts of moisture absorption. The test machines are made up of pieces such as loading frames, two crossheads, one rotating and the other stationery, and a servo-hydraulic piston that separates them. Simple static testing is done with screw-driven instruments. These devices are reasonably affordable, and their operation is less dangerous [30-32,40]. Figure 6 shows flexural strength for different specimens.

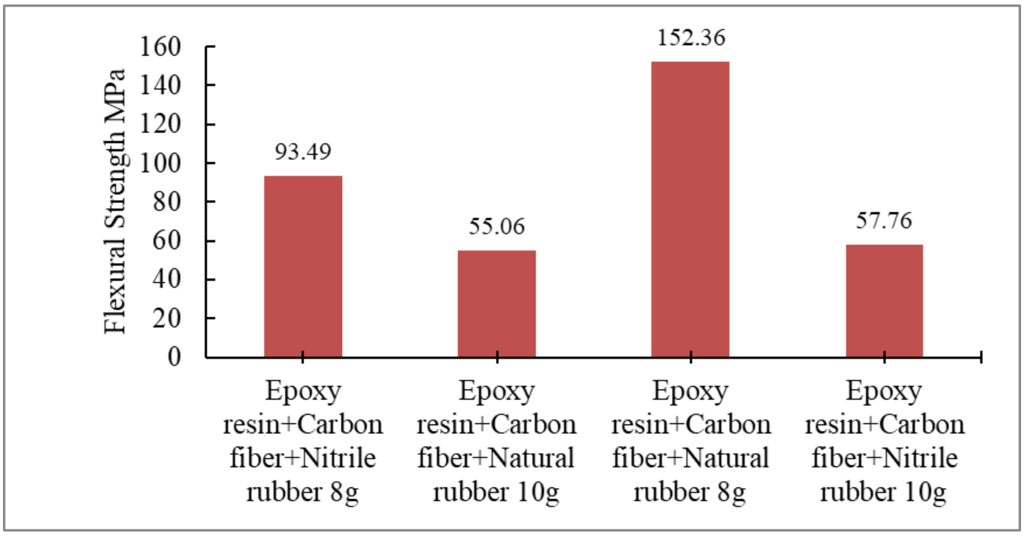

Figure 6. Different flexural strengths of different specimens [32].

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6.2. Mechanical properties.

6.2.1. Static capacity.

In normal settings, epoxies outperform aluminum alloys in terms of static strength. Composites are essentially elastic materials since fiber has a brittle nature. Elastic materials have the property of returning to their previous shape after being loaded; therefore, they reform the load on structural characteristics. Notch sensitivity is proportional to fiber modulus; as fiber modulus rises, notch sensitivity rises, and the concentration of local stresses falls. The stresses can be recovered in mild steel by using aluminum alloys and other structural metals in local yielding operations; thus, material strength loss is due to section reduction [17,30].

6.2.2. Flexural stability.

The point at which a material's tensile strength surpasses the tensile strength limit of composite epoxy is known as the flexural strength limit. The manufacturing portion is more flexible and can sustain the applied stress without breaking. The specimen for this test contains a variety of standardized values that have been arranged/specified as per ASTM and ISO standards. The specimen began to deflect throughout the test, and the test was called off when the applied load/force achieved its maximum degree of fracture. When making laminates, the ASTM standards should be followed. These recommendations are used to choose acceptable specimens for tensile testing on a universal testing machine (UTM) to determine laminate's flexural and tensile modulus. The dial indicates all of the many ways to expand for the device to expand and engage when the specimen is split; however, if the specimen cannot split, the gadget records the point where the specimen would break and elevates the stress concentration by 3.5 percent [17,23,28].

7. Challenges for Aircraft Composites

Carbon composites have a lot of advantages in the aerospace sector, but they also have a lot of drawbacks. Regarding aircraft maintenance and inspection, carbon composites in aerospace encounter the following challenges.

7.1. Barely Visible Damage (BVD).

Damage caused by BVD is described as scarcely noticeable damage. This damage is not visible to the naked eye since it’s on the inside, and a pre-flight inspection could not reveal it. The pre-flight inspection is the daily examination/detection of metal surfaces before a flight. This method tells if a metal surface is damaged but can’t tell if it’s BVD-damaged. As a result of a low-velocity impact that does not modify the metal’s surface, this damage occurs internally on the metal surface. If the damage to metal surfaces is underestimated, there is a possibility of an accident [37].

7.2. Changing the material’s qualities.

This is one of the issues that carbon composites face. The environment, such as moisture conditions, influences the component qualities of the materials we manufacture using a constituent polymeric matrix, and the constituent characteristics of the material are transformed as a consequence. Moisture causes certain metal surface cracks. These cracks are so small that they can’t be seen with the human eye; thus, they’re classified as BVD damage. Laminates comprised of composite materials also generate extremely little delamination. The temperature of the surrounding environment goes below freezing as the aircraft reaches its maximum altitude. Due to this expedition of cracks, new cracks appear, perhaps resulting in a deadly aircraft accident [37,38].

7.3. Delamination.

The delamination effect occurs when a substance fractures into different layers. Impact tests with a low-velocity drop and gas gun tests on carbon composite plates with projection at DLR, all performed at a high velocity, are used to assess delamination damage. Delamination is the main damaging mechanism when the impact energy is minimal. With more impact energy, hard bullets induce fiber damage. Delamination increases the absorption energy of composite material plates, lowering the total penetration effect. It follows the technique for impact damage analysis and modeling, which demands the use of failure models. Damage to the plane ply and damage to the delamination is included in this damage [39,40].

8. Conclusions

The review is conducted on the applications of composite for aerospace. Various Airbus utilized carbon composites in their design. It shows that carbon composite is widely used in aeronautical, housing, aeroplane, road, and car to describe materials with substantial changes in material properties that increase overall performance. The aerospace industry benefited the most from the composite. Carbon fiber offers a range of unique qualities, as evidenced by the aerospace industry. The aircraft industry has lately moved to the composites sector because of the behavior of carbon composites. It has been proved that carbon composites in aerospace save fuel, time, and energy while improving operational efficiency and reducing aircraft weight. It gives aeroplane components a tremendous amount of tensile strength. Another important aspect is the fuel economy of aircraft. Previously, aluminum was the primary foundation material in aircraft manufacturing; metal aircraft consume more gasoline during take-off and transportation; however, carbon composites are already making aircraft lighter, burning less fuel during take-off and transit. It is believed that aeroplanes made of carbon composites are revolutionary inventions. Carbon composites offer properties that allow them to be employed in various applications. As a result, it’s a forward-thinking and in-demand industry.

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Conflicts of Interest

The authors declare no conflict of interest.

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