Carbon Fiber Composites

Daddy of Lightweight Design

Introduction

The year was 1981. On the starting grid of the Formula 1 season, McLaren unveiled something that had never been seen before. The MP4/1 was the first F1 car that raced with a monocoque chassis made entirely from carbon fiber composite. It was a bold move. Some doubted its strength, while others questioned its durability. But when John Watson took victory at the British Grand Prix, it became clear that this material was a game-changer. The car was not just faster than its aluminum-bodied competitors. It was lighter, stronger, and safer. That season marked the beginning of a revolution in lightweight materials.

Lightweight design is a key principle in engineering, focused on reducing mass without sacrificing performance. The material is considered lightweight, not just because of its low density, but primarily because of its high specific strength and stiffness, and ability to meet specific design requirements through its anisotropic and heterogeneous character (Daniel & Ishai, 2006, p13). Carbon fiber-reinforced polymers, or CFRP, have become one of the most important materials in the field of lightweight design. From aerospace to motorsports, its unique properties have redefined what is possible.

This report explores how and why carbon fiber contributes to lightweight design. By examining its microstructure, manufacturing procedures, mechanical properties, and real-world applications, we aim to understand the key advantages that set CFRP apart from traditional materials. The discussion will also highlight its limitations, including directional strength, failure modes, and challenges related to damage and repairs. Using the MP4/1 as a case study, along with other examples, we will analyze how carbon fiber has shaped modern engineering and whether it is always the best choice

Theory

Discovery and First Use Case

Carbon fibers have been known to humans for more than 150 years, although its use-cases were somewhat different to today's. It was first discovered in the late 19th century for use as filament in electric light bulbs. Thomas Edison needed a filament that could last long and experimented with baking strands of cotton or bamboo in a low oxygen environment to carbonize them. This made them heat resistant and suitable for use in lightbulbs. However, when tungsten was discovered as a better alternative, carbon fiber was sort of forgotten for many years. (*A Brief History of Carbon Fiber*, 2019)

It wasn't until the 1950s and 1960s, that carbon fiber as we know it today was developed. Roger Bacon managed to create carbon fibers using a process that involved heating rayon fibers. The fibers were of 20% carbon content, which proved the process inefficient. After many attempts made by other scientists, the breakthrough came in 1963 when British scientists W. Watt, L. N. Phillips, and W. Johnson patented a manufacturing process that produced high strength carbon fibers. These fibers were the first ones that saw commercial use. (*A Brief History of Carbon Fiber*, 2019)

The first major application of modern carbon fiber was in aerospace. Due to its high strength to weight ratio it proved to be ideal for these types of applications, where weight-savings and strength has to be balanced. Rolls Royce was first with using carbon fibers in jet engine fan blades rather than titanium, to improve efficiency by reducing the inertia and the weight of the blades. However, switching material to CFRP also made the blades brittle and prone to failure under bird strikes. Despite these failures, it proved that carbon fiber composites could be a viable material for high performing industries, including aerospace, military, and motorsports. (*Carbon Fibers, 2025*)

Carbon Fibre Microstructure

To understand the structural properties of carbon fiber, we must examine it at the microscopic scale. The fibers themselves are usually 5 to 10 micrometers in diameter, composed almost entirely of carbon atoms arranged in a crystalline structure following the fibers longitudinal direction (Joshi et al., 2019). The arrangement is a hexagonal pattern similar to graphite.

The key difference lies in how the sheets of graphene are stacked. Unlike the perfectly parallel layers found in graphite, carbon fiber features a fraction of its graphene sheets crumpled and misaligned in a configuration known as turbostratic graphene (Figure 1). This disordered arrangement increases resistance along the glide planes, reducing ductility while significantly enhancing the ultimate tensile strength of the fibers.

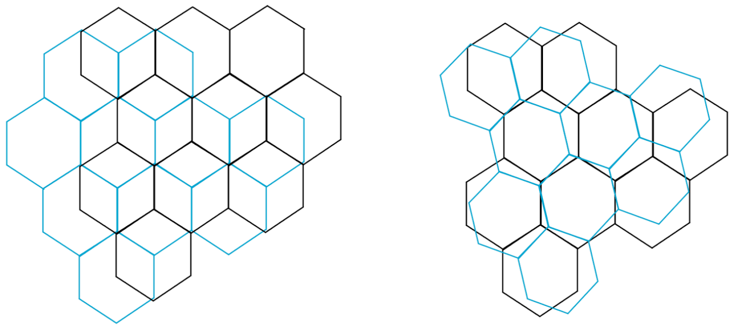

Figure 1, AB-stacked graphene (left) and turbostratic (right)

High-strength / high-stiffness materials tend to fail due to the propagation of flaws. Hence why a fiber of such a material is inherently stronger than its bulk form. Fibers, like those in CFRP's, have a diameter of a few micrometers, thus reducing the chance of flaws in the material. Adding to this, if one or a few fibers were to break the whole material would not be at risk, as failure in one fiber won't propagate to the entire assemblage of fibers. The fibers are embedded in a matrix that transfers load and shear forces, to and between the fibers, and protects them from the environment. (The Future is Advanced Plastics and Composites, u.å.)

To further optimize the strength, one can increase the lengthwise modulus of the composite, by applying knowledge of the orientation dependent properties of the fiber. Resulting in a composite-material with tremendous potential for a high strength-to-weight and strength-to-stiffness ratio over conventional materials. CFRP's can therefore be used to make tailormade parts without wasting material on needless reinforcement in load-directions that play little importance, further cutting down on weight. (The Future is Advanced Plastics and Composites, u.å.)

Formation and Processing of Carbon Fiber Composites

Individual carbon fibers are typically bundled together to form a tow, which is held together and protected by an organic coating. These tows can then be woven into fabrics, which are commonly used in combination with epoxy resin to create strong and lightweight composite materials. Carbon fibers in high performance structures are typically either unidirectional (fibers aligned in a single direction) or woven (fibers running perpendicular to each other).

When manufacturing carbon fiber composites, sheets of fiber are embedded within a polymer matrix, typically a resin or epoxy matrix. A common technique is to pre-impregnate the fiber sheets with resin before moulding them under high temperature and pressure. Alternatively, fibers can be manually laid onto the mould, with resin applied using a brush (formlabs, n.d.). Both of these manufacturing methods generally require the use of a mould, either a positive or negative mould, depending on which side requires the higher precision. The use of a mould imposes larger restrictions on part geometry in comparison to traditional machining methods, as the part will be limited by both the manufacturing of the mould as well as the composite part itself. The manufacturing of CFRP parts also requires significantly more time in comparison to traditional manufacturing methods. As the manufacturing of the mould in addition to preparation of the mould, must both be taken into account for the total time required for manufacturing (formlabs, n.d.). Back in 1981, the MP4/1 monocoque was assembled using five flat faced CFRP components, as they lacked the modern manufacturing methods and knowledge on how to make curved panels (McLaren, n.d.). Another benefit of the CFRP monocoque was a reduction in the number of components, from around 50 to just 5, three bulkheads, the shell, and the reinforcing structure. Thus removing a number of rivets and welds, not only removing weight, but also points prone to failure. (Piola & Somerfield, 2022)

Mechanical Properties

A significant strength of CFRP is the customizability of the composite, as the fibers and the matrix can be chosen based on the desired application. As can be seen in Figure 2, different types of fibers have different mechanical properties. Properties that can be tailored for the application. In this regard choosing your fiber can be like choosing your alloy, if you know the criterions you must meet, you can choose a material that is neither underperforming or overperforming, thus optimizing cost. The variation in fibers can also be utilised within a laminate itself, as the laminate can be composed of a combination of different fibers if desired.

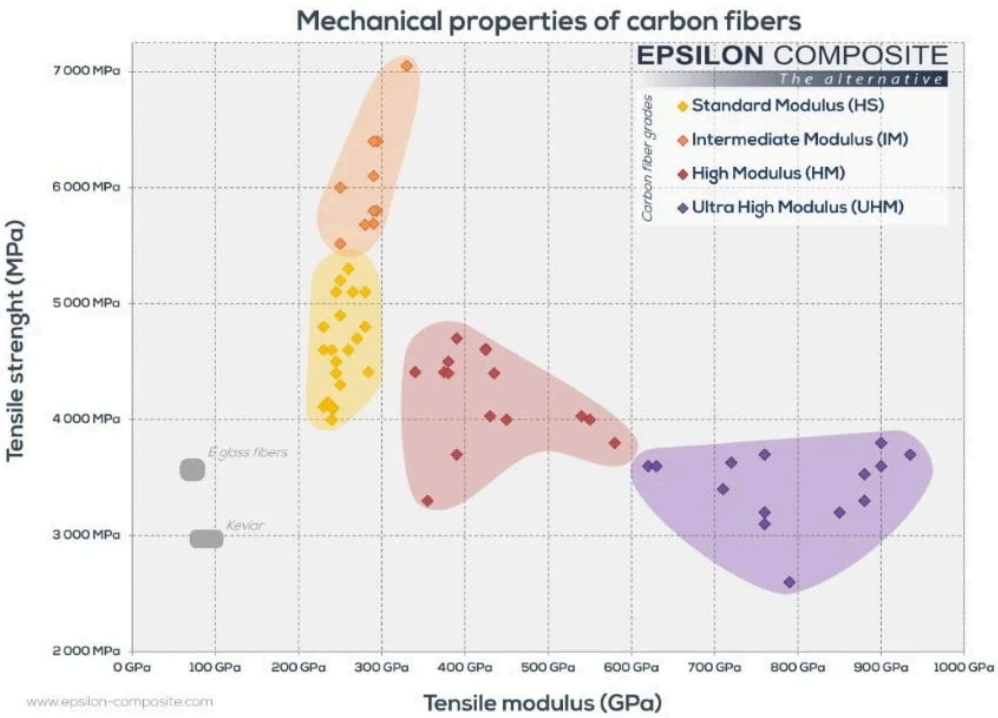

Figure 2. Stiffness and strength of different types of carbon fibers. (EPSILON COMPOSITE, n.d.)

A key property of CFRP is its anisotropic nature. The mechanical properties vary depending on the fiber orientation, allowing engineers to tailor mechanical properties to specific applications, reinforcing strength in required directions while minimizing weight. An example of this is with modern Formula 1 front wings, where the wing can be designed to withstand the scrutineering requirement, however deflect as desired when put under aerodynamic loads.

Another major strength of CFRP is its usage in composite sandwich structures. By doing a simple comparison with the bending stiffnesses of a sandwich beam and a monolithic rectangular cross sectional beam, it can be seen that the specific stiffness of a sandwich beam is significantly increased by an increase in core thickness (Figure 3) relative to the monolithic beam. Combining this effect with the freedom of fiber selection, and its anisotropic nature gives rise to an incredibly powerful material to design lightweight structures.

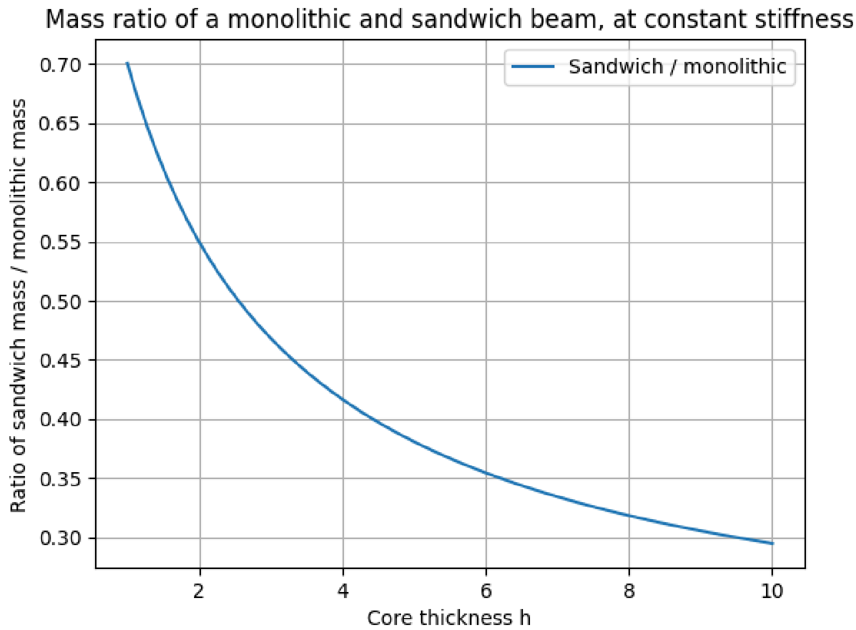

Figure 3. Mass ratio of a sandwich and monolithic beam as a function of core thickness.

Limitations

Brittleness

Damage and repair are usually much more complex with CFRP than with metals. One of CFRPs biggest enemies are impacts. The brittle nature of the material makes it not want to elastically or plastically deform, making damage very hard to spot with the naked eye. Typically, the damage is below the surface, from cracking to delamination, and is also very dependent on the production quality. Though there are methods to inspect damage like ultrasound or x-rays, even repairing can be a big hassle. CFRP cannot be welded, reshaped or joined like metals, but rather repatched by cutting out damaged parts and adding new ones. This can result in weak bonding and stress concentration at the patch. Specialized equipment is needed for well-controlled curing, adding time and cost. So damage repair is definitely possible and is a practice today, but it is certainly a complex process requiring people with extensive experience and knowledge within the field. (Addcomposites, 2024)

Fatigue

Pretty much every component part of a machine or structure will experience some kind of cyclic loading during its lifetime. Fatigue is avoidable, also for CFRP. But compared to many metals, the fatigue resistance of CFRP is quite high. The challenges come with prediction and lifetime estimations. CFRP and composites in general often fail very abruptly with no warning in an event of fatigue. It is harder to predict and require extensive monitoring of components subjected to fatigue due to the damage being hidden inside the material. This makes it harder to develop good models for lifetime estimations. They do exist but are quite advanced and still developing (Malekinejad et al., 2023).

First application in racing

Considering the advantages of CFRPs as stated above, it is clear that this is a material well suited for lightweight and high performance applications. Based on an interview with John Barnard, the chief designer of the MP4/1, the combination of a narrow chassis, yet a stiff one was desired, making the need for a new material apparent.

One of the issues was the chassis which needed to be very narrow, and that inevitably, would have lost torsional strength and bending stiffness, things like that. So I started thinking how I would make a chassis that would be narrow and yet maintain all those other elements. (Elson, 2023)

From a vehicle dynamics perspective, the stiffness of the chassis is paramount to achieve the desired handling characteristics, as to achieve 80% of the desired tuning

effects, the chassis torsional stiffness should approach the values of the total roll stiffness of the vehicle (Seward, 2014, p.34). The McLaren MP4/1, with its revolutionizing CFRP monocoque, was a car that offered the desired chassis stiffness, while maintaining low mass. With a narrow profile facilitating enhanced aerodynamics. Furthermore, thanks to the high specific stiffness of CFRP (~2.4 times that of aluminium for a high modulus twill composite), the mass required to achieve a desirable torsional stiffness was lower than that of the traditional aluminium monocoques. This resulted in a lighter vehicle, improving performance in all aspects of racing. Examples being reducing wear, especially for the tires, and cutting down on fuel consumption.
The introduction of the carbon fiber composite monocoque also greatly improved safety for the drivers, as demonstrated during the Italian GP in 1981, where driver John Watson crashed on lap 20. The car was split in two, but Watson came unharmed from the crash (McLaren Racing, n.d.)

Conclusion

Carbon fiber has evolved from an early discovery as a filament material, to one of the most advanced lightweight materials in modern engineering. Its unique microstructure and manufacturing methods have enabled the creation of lightweight, yet extremely strong composite materials. One of the greatest advantages of carbon fiber composites are its exceptional specific stiffness and strength properties, making it an essential material for lightweight design. Additionally, its manufacturing process allows for great geometric flexibility through the use of sandwich panels, enabling engineers to optimize structures by tailoring shapes to achieve the required strength with minimal mass.
This is particularly evident in motorsports and aviation, where reduced mass directly translates to improved performance. The use of carbon fiber in Formula 1 cars, as demonstrated by the McLaren MP4/1, showcased how a stiff and lightweight chassis can enhance aerodynamics, handling, and crash safety. Despite these advantages, carbon fiber presents challenges, including its brittleness, complex repair processes and difficulties in predicting fatigue life. Carbon fiber has transformed industries by enabling lighter, stronger, and more efficient designs. Ongoing advancements in

material science and manufacturing will ensure its continued role in creating high-performing and sustainable solutions.

References

Joshi, K., Arefev, M. I., & Zhigilei, L. V. (2019). *Generation and characterization of carbon fiber microstructure in atomistic simulations*. Retrieved February 20, 2025, from *https://compmat.org/articles/Carbon19.pdf*

Addcomposites. (2024, September 26). *How to Identify the Defects and Damage in Composites Materials and Structures?* Addcomposite. Retrieved February 19, 2025, from https://www.addcomposites.com/post/defects-and-damage-in-composite-materials-and-structures

A Brief History of Carbon Fiber. (2019, June 25). DragonPlate. Retrieved February 19, 2025, from https://dragonplate.com/a-brief-history-of-carbon-fiber

Carbon Fibers. (2025, January 30). Wikipedia. Retrieved February 19, 2025, from *https://en.wikipedia.org/wiki/Carbon_fibers*

Daniel, I. M., & Ishai, O. (2006). *Engineering Mechanics of Composite Materials*. Oxford University Press.

EPSILON COMPOSITE. (n.d.). *The different grades of carbon fiber*. Epsilon Composite. Retrieved February 19, 2025, from https://www.epsilon-composite.com/en/carbon-fiber-grades formlabs. (n.d.). *How to Manufacture Carbon Fiber Parts*. Formlabs. Retrieved February 19, 2025, from https://formlabs.com/eu/blog/composite-materials-carbon-fiber-layup/

Malekinejad, H., Carbas, R., Akhavan-Safar, A., Marques, E., Sousa, F. C., & da Silva, L. (2023, September 28). Enhancing Fatigue Life and Strength of Adhesively Bonded Composite Joints: A Comprehensive Review. *Advances in Service Life Evaluation of Metallic and Composite Materials*, *16*. Retrieved February 17, 2025, from https://www.mdpi.com/1996-1944/16/19/6468

McLaren. (n.d.). *MP4/1*. McLaren Heritage. Retrieved feb 18, 2025, from https://www.mclaren.com/racing/heritage/formula-1/cars/1981-formula-1-mclaren-mp4-1/

Seward, D. (2014). *Race Car Design*. Bloomsbury Academic.

Piola, G. Somerfield, M. (2022, jan 15). *The McLaren that changed Formula 1 history, motorsport.com.* https://www.motorsport.com/f1/news/the-car-that-changed-formula-1-history/4779400/

The University of Tennessee Knoxville. (n.d.). The Future is Advanced Plastics and Composites. https://fcmf.utk.edu/future-advanced-plastics-composites/