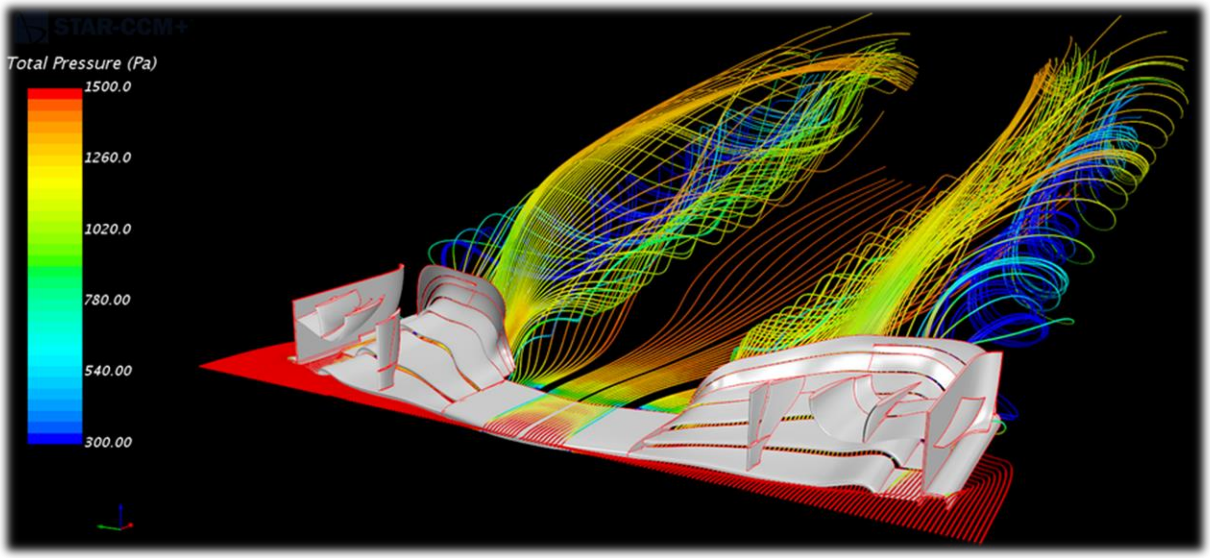

Figure 1: CFD simulation depicting pressure pathlines of air passing through a front wing.

The Development of Flexi Wings in Formula 1

3B4: Mechanical Engineering Materials

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Contents

Summary:

The following report will investigate the development of 'flexi-wings' in Formula 1. The front wing is an essential component of an F1 car, influencing areas such as downforce generation, airflow management, ensuring car balance, drag management, and much more. Formula 1 cars have undergone drastic change throughout the years, going from a simple chassis with wheels and an engine, to automotive phenomena that are constantly pushing the boundaries of multiple aspects of physics. The aerodynamics now play perhaps the most important role in ensuring that maximum performance can be attained. Fluid mechanics, material science, and many other highly quantitative subjects combine to produce technology that is at the forefront of the automotive industry.

This report primarily focuses on the development of the front wing rather than the rear wing, and its ability to flex under increased aerodynamic loads. Engineers implement this design feature in order to maximise aerodynamic performance by reducing drag or increasing downforce where necessary. These physical changes to a car's shape can be attributed to the physical characteristics of performance grade composite material such as carbon fibre reinforced polymer (CFRP). This is a composite constructed from carbon fibres which are embedded in an epoxy resin. The fibres have a high strength modulus, giving the material an unparalleled strength to weight ratio. Functionally graded materials such as CFRP can be manipulated through design so that they can perform as required in different situations.

The area of 'flexi wings' has been a controversial topic throughout the years of Formula 1. The report details the history of aerodynamics, the technical regulations surrounding front wing design, a CFD analysis of different wing designs, the material science behind CFRP and its manufacturing processes, a quantitative analysis of the flexing phenomenon, how CFRP can be reused, and all of the controversies surrounding the development of 'flexi wings' in Formula 1.

Background of Formula 1:

Formula 1 is one of the world's fastest sports. Across the globe, 20 cars take to the grid 24 times a year to compete for first place. Each team has two drivers and two cars. A points system is used to determine the where the teams are placed on the leaderboard. At the end of the season, the team with the most points wins the Constructor's Championship, and the driver with the most points wins the Driver's Championship.

The drivers need to be at the top of their game, and so does the technology. The cars are at the pinnacle of engineering and are constantly having to adapt to ever-changing situations in a highly competitive field. Each team is always trying to develop the latest and greatest technologies, to gain even the finest of margins on their competitors; because, in a sport like this, even the smallest bit of improvement can shave milliseconds off race times – which as we have seen in the past, can influence championships. Complex subjects such as aerodynamics, electronics, material science, and thermodynamics all come together in unison to try and produce a lap time that is better than the one next door to them in the pit lane.

Importance of Aerodynamics in F1:

Aerodynamics is a branch of fluid mechanics that describes the motion of solid bodies through air and how they interact. It is an essential component of F1 vehicle design as it can influence performance massively. Factors such as drag, downforce, and temperature control can all be impacted by how a car's aero is designed. Ultimately, engineers want to find an optimised balance between the amount of downforce and drag generated by the car. However, due to each F1 track having different dimensions, and the same track having multiple different bends and straights, the car needs to be able to perform at each section of the track, without compromising on performance at other parts. Each car has a variety of different aerodynamics components, that all play significant roles in performance optimisation.

The goal is to develop a suitable aerodynamic package where airflow is optimised, balancing the velocity, downforce and stability around the car. The car needs a lot of downforce, but also a minimal amount of drag at high speeds to ensure performance is optimised. Downforce is a vector property that essentially pushes the car into the track. This allows for greater tire grip, allows for faster cornering, and ensures that the car doesn't fly off the track. This force is created through the front and rear wings of the car. These wings are shaped like inverted aeroplane wings, creating low pressure below the car, and high pressure above it. The rear wing's main role is to provide stability by creating high downforce over the rear tires. The front wing creates a downforce at the front of the car, preventing the nose of the car from lifting off the track. It also controls the total airflow around the F1 car, allowing it to be directed in different ways. Too much downforce at the rear of the car causes understeer, causing the car to struggle when turning. Too much downforce at the front of the car causes oversteer, causing the rear tires to lose grip.

Figure 2: [Rear wingtip vortices on a McLaren F1 car.]

These two wings work in harmony with the diffuser. The diffuser is located at the rear on the car's underside. Based on Bernoulli's principle, the diffuser accelerates the air flowing under the car, creating a low-pressure zone which increases the downforce. The diffuser plays an important role of generating efficient downforce while minimising drag. It is responsible for a phenomenon known as 'ground effect' which sucks the car to the ground. The ground effect maximises downforce while managing drag efficiently.

The ideal scenario is for the car to be able to generate high downforce when cornering and turning, and experience negligible drag when on the straights. However, this ideal scenario is not possible, due to constraints by the laws of physics, and the regulations put in place by the FIA (Fédération Internationale de l'Automobile). This is where Formula 1 engineers had to become creative. They needed to develop an aero design that allowed them to manipulate airflow better than their competitors, without breaching the regulations put in place. This is where we saw the introduction of the flexi wing concept across the grid.

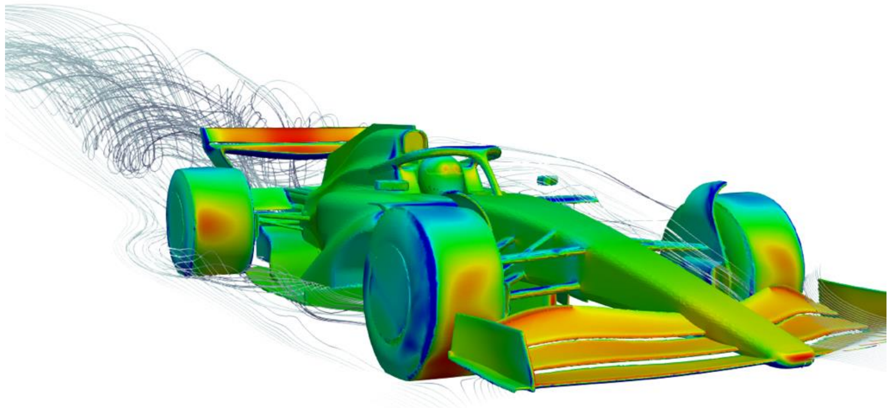


Figure 3: CFD simulation showing pressure contour of a F1 car travelling at high velocity.

Overview of the Flexi Wings Concept:

In order to achieve the ideal scenario of minimised drag yet high downforce at different parts of the track, the engineers had to look outside of the box. They knew they were not allowed to infringe the FIA's regulations, so they looked at 'bending' them instead. The flexi wings concept utilises the physical properties of carbon fibre to bend the wing about its vertical axis. This allows the dimensions of the wings to change shape by a significant amount when they experience a high degree of loading and return to their normal shape when the load is no longer applied.

At high speeds, the material is under a high amount of stress. This causes the wings to deflect slightly due to the high g forces being exerted on the car's body. Typically, this horizontal force will cause the wing to take a flatter position, which results in lessened drag compared to when it is in its original angled position. As the car reaches higher speeds, the horizontal force decreases the angle of attack that the airfoil rests at, which allows air to bypass the wing at a higher velocity, and hence a lower pressure. This causes the drag to be minimised and the airflow is given a more direct path to bypass through the vehicle's bodywork.

This phenomenon can be achieved thanks to the properties of carbon fibre composites. Carbon fibre composite is a material with an excellent strength to weight ratio. It is brittle and corrosion resistant, yet stiff. However, the carbon fibre can be engineered in a specific way to allow for the aerodynamic flexibility that was discussed above. When the wings are being assembled, the way in which the sheets of carbon fibre are layered can determine where and how the wing flexes.

Engineers use this tactic to manipulate the wing in certain ways when subjected to aerodynamic loads, which can have significant performance benefits for the car.

Where the controversy of this flexing phenomenon lies is in the testing. Each team tunes how much their wings flex so that they stay within the regulations put in place by the FIA. The FIA carries out static load tests which examine the wings deflection when subjected to a linear static load. Recently, many teams have found ways to design the wings so that they just about pass the static load tests, but flex further when aerodynamic loads are applied at high speeds during the race. This has caused major controversy so far in the 2024 F1 season, but we will discuss this later on in the report. In the image to the right, we can see that the rear wing angle of attack decreases significantly when met with a high-speed airflow.

Figure 4: Drawing depicting a Red Bull RB19 rear wing flexing under aerodynamic load.

Evolution of Wing Design:

In the year 1792, English engineer, Sir George Cayley started work on a concept he called, "The Lift Generating Inclined Plane", modernly known as the wing. In 1903 this technology was further developed. Famously, the two Ohio brothers, Orville and Wilbur Wright took to the skies via powered flight. This was the moment where wing design was revolutionised. Fast forward to the mid-1960s, Jim Hall, an American race car driver, engineer, and team owner was the first to put a wing on a race car. He is considered to be a pioneer of the use of wings, moveable aerodynamic devices, and the composite monocoque chassis on race cars. Rather than take the approach of an aeroplane wing, creating lift, Hall inverted the angle of attack so that the wing would produce a negative lift (otherwise known as downforce). [1]

The idea of a wing on a Formula 1 car was first conceived by Lotus F1 Team on Graham Hill's 1968 car during the Monaco Gran Prix. His Lotus 49 was fitted with a front and rear wing. This design change proved to be a huge success, landing Hill pole position in qualifying and a race win on the Sunday. This was noticed by other teams such as Ferrari, who took note and began work on their own wing designs. Since then, it has become one of the most complex and important elements of on a F1 car.

Figure 5: Front wing of the 1968 Lotus F1 car in Monaco

Regulatory Changes Over Time:

Figure 6: Front wing design changes throughout the years.

As the years went on, the front wing design became more and more complex. Starting out as a flat wing mounted to ahead of the front tires, the wings were soon placed on stilts, creating large amounts of downforce by cutting through clean air. This design was soon banned after both Lotus cars suffered wing failure in the 1969 Spanish Gran Prix, resulting in catastrophic crashes. The FIA declared that the wings had to be bolstered to the bodywork of the car from then on. This regulation caused the entire shape of the F1 car to be sculpted into the design we see today. However, it wasn't long before teams began to find loophole in the regulations. From the mid 80's the use of carbon fibre was adopted by most teams for their wing design due to its suitable performance characteristics. In 1997, Tyrell Racing found a way to mount small little wings on stilts. This design was known as the "x-wing". The FIA intervened and banned the design the following year. Once again, the science of aerodynamics was revolutionised thanks to technology led by the aerospace industry. Wind tunnels and computational fluid dynamics (CFD) simulation led to wing design becoming increasingly more complex. A key moment in wing design was during the 2008 season. The level of complexity in the wing design was something never before seen on the grid. Different types of canards, channels, flaps, winglets, and turning vanes were added to the wings. There was a lack of standardisation in wing design across the grid which made the FIA address the issue. These wings benefited the cars that wore them but created a high amount of turbulence behind the car resulting in a worsened racing experience in terms of wheel-to-wheel competition. Once again, the FIA stepped in and added more regulations such as increasing the wing width.

From 2012 to 2019 the number of components on the front wing were reduced. Further wing regulations were implemented by the FIA in 2019 and 2022. This was all done in an effort to reduce the vortices and the turbulent wake generated by the cars. The new designs aimed at directing the flow of the air over the front tires, rather than pushing it out beyond the sides of the car. In 2024, the front wing now has a wider, more triangulated shape, with less components and larger endplates. [1]

2024 Technical Regulation Updates:

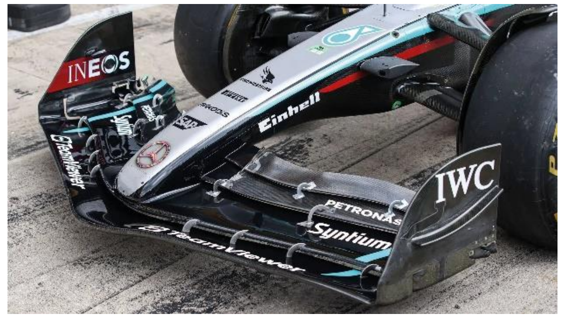


Figure 7: Mercedes-AMG Petronas F1 front wing.

The following data and information was acquired from multiple sources: the FIA 2024 Formula One Technical Regulations Document [2], and F1 Blast [3], a reputable motorsport journal that stays up to date with all things current affairs related in Formula 1.

- 150mm increase in front wing width, now reaching the maximum body width (2m).
- Front wing flaps raised by 150mm from previous rules.
- Removal of complex bargeboards and tiny aero devices around the front wing.
- Deflection cannot exceed more than 5 mm.
- Increased front wheel wake control through expanded wheel fairings.
- There must be no more than 4 closed sections.
- The distance between adjacent sections must lie between 5 and 15 mm at closest position.

The flexibility of Front Wing Bodywork will be tested by applying a load of [0, 0, -1000] N at points [XF, Y, Z] = [-800, ±800, 250] or [-1000, ±800, 250]. The load will be applied in a downward direction using a 50mm diameter ram on a rectangular adaptor measuring 350mm in the X-direction and 150mm in the Y-direction. This adaptor must be supplied by the team and should:

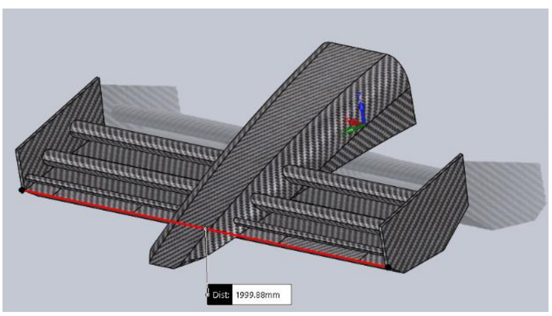
1) Have a flat top surface without recesses.
2) Be fitted to the car so as to apply the full load to the bodywork at the test point and not to increase the rigidity of the parts being tested.
3) Be placed with the inner face 725mm from Y=0.
4) Be placed with its forward face at XF=-1100mm.
5) Be placed with its top face at Z=250
6) Have a mass of no more than 2kg.

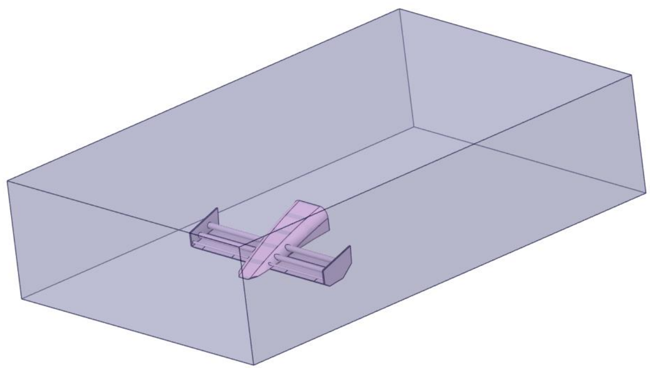
The deflection will be measured relative to the survival cell and along the loading axis. When the load is applied symmetrically to both sides of the car the vertical deflection must be no more than 15mm. When the load is applied to only one side of the car the vertical deflection must be no more than 20mm. This data is per Article 3.15.4 of the 2024 FIA Formula 1 Technical Regulations.

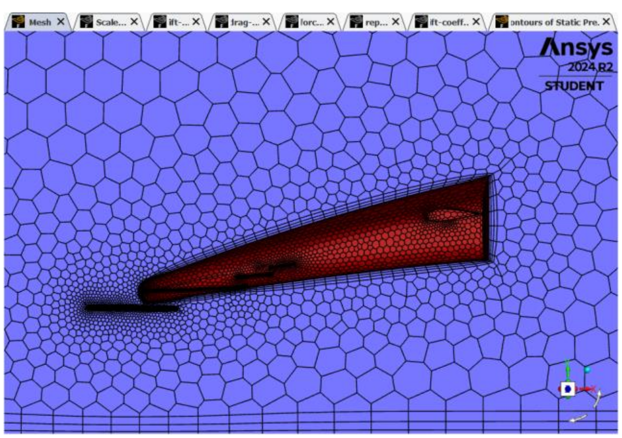
CFD Simulation of a Carbon Fibre Front Wing:

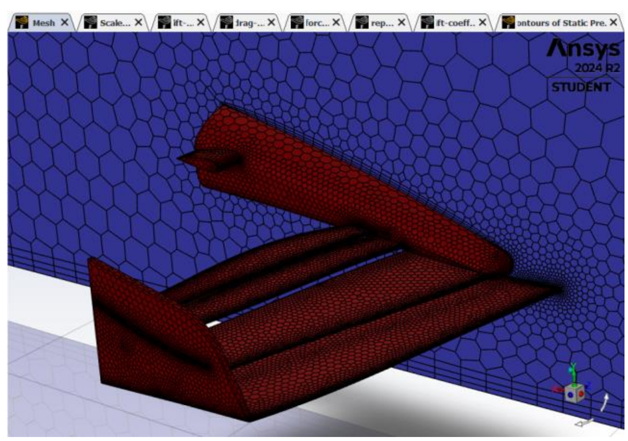
The following section of the report includes two computational fluid dynamics (CFD) simulations that I carried out. I ran these simulations so that I could collect some of my own data and better understand the effects that aero has, rather than pulling it from online websites. I also wanted to compare how two different wing designs manage airflow of the same velocity. In order to do this, I used SolidWorks and ANSYS. I downloaded two front wing CAD designs from GrabCAD, an online CAD repository. One wing is based off the 2022 Aston Martin Racing F1 team's design [4], while the other is a simple flat-plane wing front wing with simple design elements [5]. The designs were imported to ANSYS Workbench, where I created enclosures to simulate high velocity airflow. Two meshes with the same conditions were generated around the wing structures and horizontal airflow was directed at the wing. This airflow was set to 300 km/h (83.3m/s) to best simulate an F1 car nearing maximum velocity on a straight part of a circuit.

The below images show the flat-plane carbon fibre wing design rendered in SolidWorks, the flat-plane wing inside the enclosure on ANSYS DesignModeler, and the poly-hexcore mesh of the 2022 wing generated in Ansys Fluent.





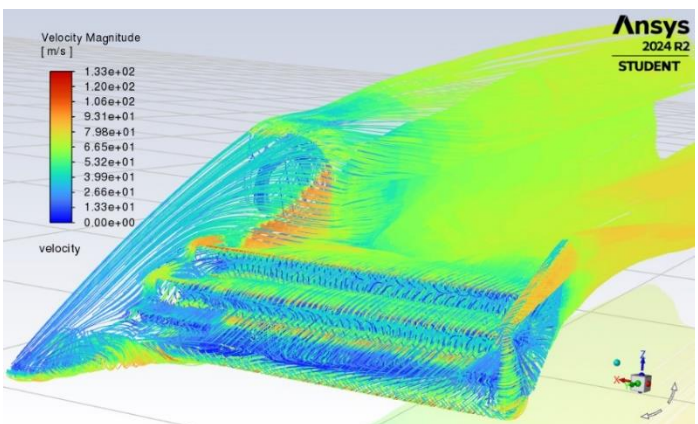


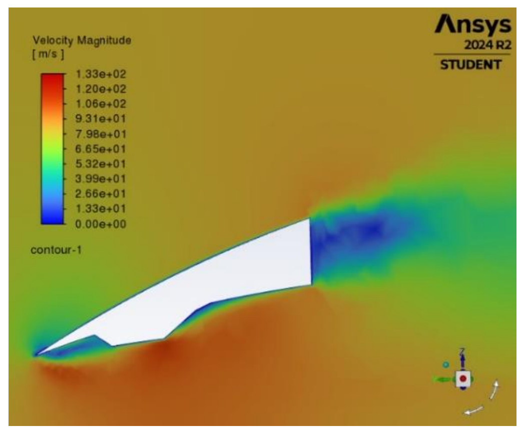


A large amount of quantitative data was generated from this analysis. When running the solutions, I was able to produce multiple contours and pathlines which gave graphical displays of how the wing interacts with oncoming aerodynamic force, velocity, and pressure. These visualisations can then be used to show how much strain the carbon fibre composite endures at one part of the wing, relative to the whole body.

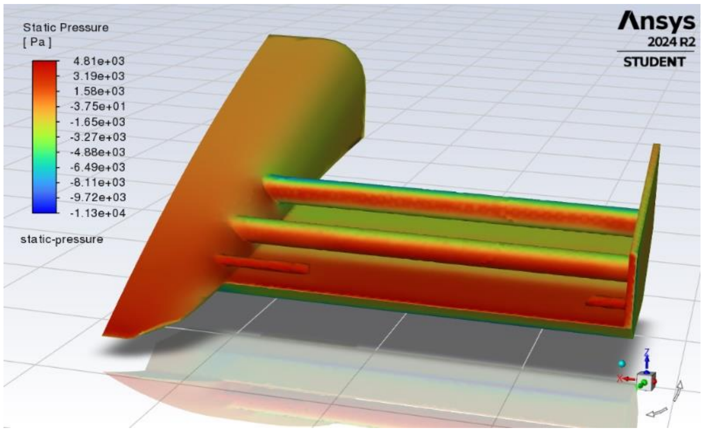
CFD Analysis of a Simple Flat-Plane Front Wing:

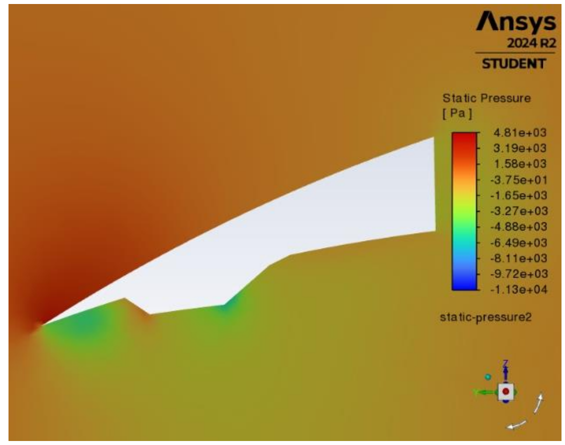
For the flat-plane wing, the below images show how oncoming high-velocity air at 300kmph interacts with the wing. The greatest velocity passing through the wing is 133 m/s (478.8 km/h). Despite simulating airflow at 300 km/h, different components on the wing can cause even greater airspeeds to be generated due to lower and higher-pressure zones. The higher velocity regions are denoted by the orange-red spectrum. The lower velocity regions range from the blue to the green. The air velocity is inversely proportional to the pressure acting on the wing, related by Bernoulli’s Principle. We can also see how the wing helps to direct the airflow. The smooth edges on the flaps work to ensure that the airflow can cascade off the back of the wing and be directed beneath the car into the diffuser. Another observation is how the endplate works to reduce the vortices generated by the wing tips, reducing turbulent airflow behind the car.





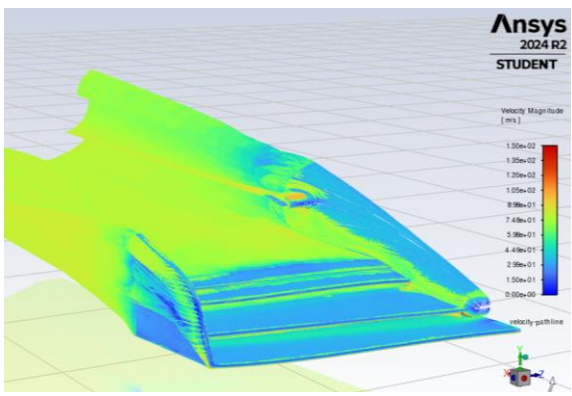
The static pressure can also be displayed graphically. This image displays the air pressure acting about the wing. The high-pressure zones act on upper parts of the wing, which leads to high downforce generation. This graphic from the simulation illustrates the static pressure distribution across the front wing at 300 km/h. The orange and red sections represent high amounts of static pressure while the green and blue regions represent low or negative static pressure (suction). If I used a wing model that was more similar to a modern F1 car in the simulation, there would be much more blue and green elements below the car as the wing design would have been more aerodynamically advanced.

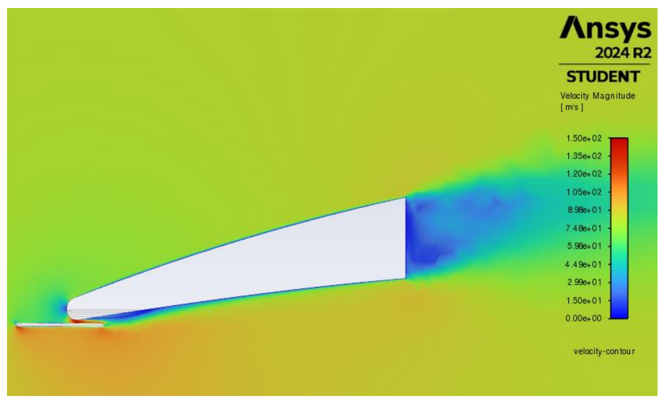




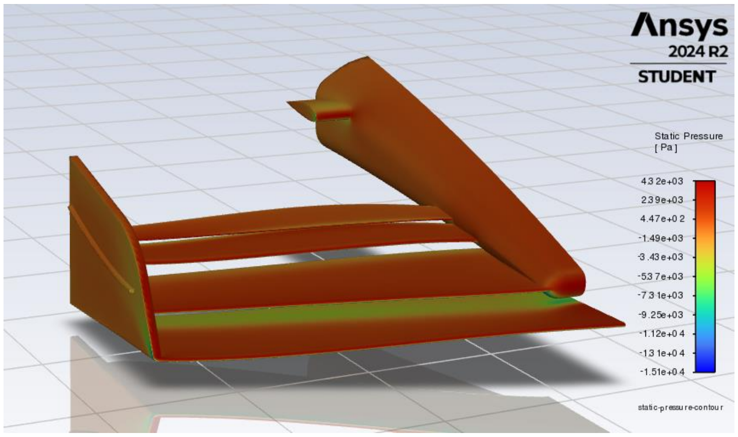
CFD Analysis of a 2022 Front Wing:

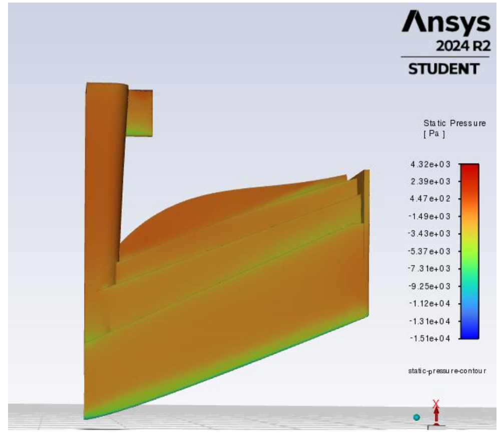
The second CFD simulation I ran was using a design based on the 2022 front wing regulations. Compared to the flat-plane wing, the 2022 version is much more aerodynamically advanced, reducing drag, yet with the ability to produce more downforce.





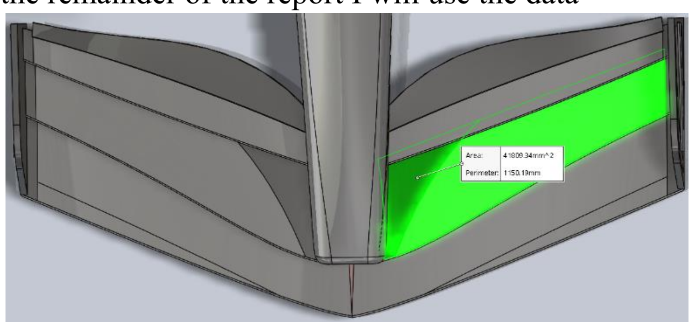
The above images display the velocity profile across the wing in the second simulation using a 2022 wing. The airspeed distribution is much better compared to the flat wing. This wing is much more effective at slowing down the airflow, leading to greater downforce generation. The airflow also cascades off the wing and endplates at a lower overall velocity and in a much less turbulent fashion. This enables other aerodynamic components such as rear wing and diffuser to manage the airflow in a more efficient manner. There is also a noticeable airspeed difference between the flow on the top of the wing versus the underside, as shown by the velocity contour on the right. The air velocity on the bottom is approximately 90 – 100 ms^{-1} (324 – 360 km/h), an increase on the inlet velocity that was set to 300 km/h. The air velocity on the top is travelling at a reduced speed of approximately 45 ms^{-1} (162 km/h).





The above images display the static pressure contours across the front wing. Compared to the flat wing design, there is once again a much better even distribution. The pressure on the top is much more uniform, and much greater overall. The pressure on the underside of the wing is also distributed much better and is significantly lower. This increased pressure means the wing generates a much higher downforce per unit area. The performance characteristics of the wing's material (carbon fibre reinforced polymer) needs a much higher load bearing capacity due to this pressure distribution, and also due to the wing being thinner and more aerodynamic compared to the flat wing.

Downforce and Drag Force Calculation:



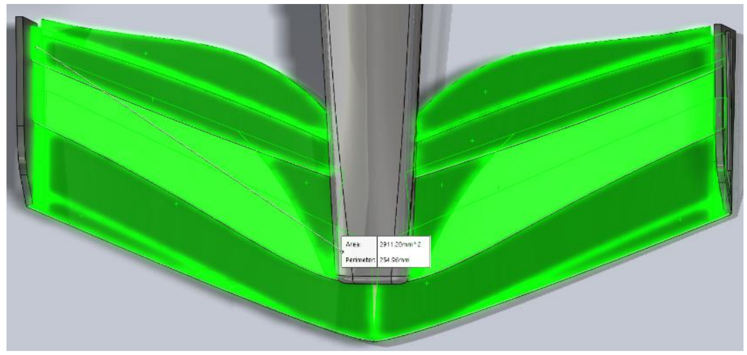
For the sake of accuracy and relevance, for the remainder of the report I will use the data generated by the 2022 wing CFD simulation. As we can see in the above pressure contour, the pressure on the middle flap is very evenly distributed. We can therefore use this section to analyse the mechanical properties of the wing. From the pressure contour, we can see that there is a slight gradient ranging from deep red to a fainter orange colour. Judging from eye we can approximate an average value of around 2500 Pa acting on the cross-sectional area. We can use this to calculate the force acting on the area.

$$F = PA = 2500(0.04180934) = 104\ N$$

Therefore at 300 km/h that section of the wing generates approximately 104 N of downforce. If we wanted, we could simulate the total aerodynamic load or downforce using the following:

$$F_{downforce} = \frac{1}{2}\rho v^2 C_L A$$

Where C_L is the coefficient of lift and ρ is the density of the fluid (air).



From the 2022 front wing simulation, the Ansys software was yielding -7.6 for the coefficient of lift. Typically, the lift coefficient ranges from around 0.9 to 1.5, but according to a research paper published, it was found that C_L equalled 1.22 for a wing with an angle of attack at 9° [6]. Obviously, the geometric properties of the wing tested are different to the one I used to simulate. For the sake of the report, I will still use -7.6 as the drag coefficient. From testing it out it yields a valid downforce value. The above area represents the cross-sectional area of the flaps, the main contributing parts of downforce generation. Summing up the area of all flaps it came to 0.7178979 m^2. Taking an average velocity of 42.5 ms^{-1} across all of the wing flaps, we can calculate the downforce:

$$F_{downforce} = \frac{1}{2}(1.225)(42.5)^2(7.6)(0.718) = 6037\,N \quad \rightarrow \quad m = \frac{F}{a} = \frac{6037}{9.81} = 615\,kg$$

Therefore, for airflow travelling across the front wing at 45.5 ms^{-1}, 6037 N or 615 kg of downforce is generated. This figure does not include some of the aero components such as nose cone or end plates, in real life a front wing would be expected to produce more downforce. The current minimum dry weight for a Formula 1 car in 2024 is 796 kg, as per the FIA technical regulations [2]. This means that at speeds of 300 kmph, the front wing alone can produce a downforce almost the same weight as the car.

The drag force can also be calculated from the CFD simulation. The drag coefficient yielded from the simulation was approximately 1.619. The formula for drag is given by:

$$F_{drag} = \frac{1}{2}\rho v^2 C_d A$$

Where C_d is the coefficient of drag.

$$F_{drag} = \frac{1}{2}(1.225)(42.5)^2(1.619)(0.718) = 1286\,N \quad \rightarrow \quad m = \frac{F}{a} = \frac{1286}{9.81} = 131\,kg$$

From the CFD simulation, we can see how the front wings have to withstand an extreme amount of aerodynamic stress at high speeds. This is an extremely important performance characteristic in how the flexi wing concept is optimised and used by teams in a race setting. From the data generated by the CFD simulations, we can calculate various metrics such as wing deflection, bending stresses, strain, and failure mechanics.

Applications of Carbon Fibre Reinforced Polymers in F1:

Strictly speaking, a composite structure is any structure made of more than one material. In motor racing it is commonly used to refer to any large component made out of carbon fibre, often containing inserts of aluminium or titanium [7]. Formula 1 relies heavily on carbon fibre composites, so much so that aside from the engine and gearbox, 85% of the car is constructed from the material [8]. Carbon Fibre Reinforced Polymer (CFRP) is a composite material made by layering carbon fibres and embedding them inside a thermosetting plastic such as polymer resin. Since its introduction by McLaren in 1981, it has always played a significant role in Formula 1. It has many desirable material properties, such as high strength, light weight, no corrosion, high stiffness, low density, and excellent fatigue and creep resistance, making it very suitable for many applications of Formula 1. Despite this, CFRP also has its disadvantages that Formula 1 engineers must account for. It is a very brittle material which gives it low impact and fracture toughness. Its compressive strength is also less than its tensile strength, which is a property that must be accounted for in wing construction to prevent certain parts buckling under aerodynamic loads.

It also has anisotropic properties, which in the case of CFRP, means that it is strong and stiff in the direction of its fibres, but weaker in any other directions. Engineers can take these properties and manipulate them to perform as desired. CFRPs can be divided into two classes: those with long fibres (continuous fibre reinforcement), and those with short fibres (discontinuous fibre reinforcement). For composite with continuous fibre alignment, it is assumed that the load is transferred directly to the fibres, and the fibres in that direction are the principal load-bearing constituents. The polymer matrix is used to support the carbon fibres, ensuring that the structure does not change shape on a microscopic level. In Formula 1, the matrix is most commonly made of a thermosetting polymer, particularly epoxy. Thermosetting polymers are resins which cross-link during curing into a glassy, brittle solid. These polymers are usually polyesters and epoxies [9].

Figure 8: A 2017/18 front wing design showing the orientation of carbon fibres within the composite.

The anisotropy of the carbon fibres within the resin means that when the composite material is met with certain stresses, depending on which way the fibres are orientated relative to the load direction, the surface deflection will not be constant for all directions. When a force meets the material in the direction that the fibres are aligned (parallel to the fibres) maximum material strength and stiffness is observed. When the force meets the material perpendicular to the fibre alignment, the surface may flex, due to it being weaker and more ductile. This 'flexing' phenomenon can lead to less aerodynamic drag on the straight parts of a track where the car aims to reach maximum velocity, without compromising on downforce when slowing down and cornering. The fibres of different components of a wing are orientated in different directions, leading to some parts flexing more than others under the same load.

In the above image, after close inspection, many of the different components on the wing have carbon fibres which are orientated in different directions, but they are aligned continuously and in the direction of the aerodynamic loading experienced. This allows for a higher load bearing capacity.

The way in which a piece of carbon fibre reinforced polymer is manufactured can also determine the performance characteristics of the material. As we have covered in 3B4 lectures, the fibre length and thickness can massively impact many physical properties of a material. Increased fibre length can improve strength, toughness, fracture resistance, stiffness, impact resistance, fatigue resistance, and thermal/electrical conductivity. Meanwhile, shorter fibres can improve the overall ductility of the material and are easier to manufacture into complex shapes. The same relation can be given between thick and narrow fibre diameters. Thicker equals stronger etc. We can see the effects of this all over a F1 car. Aerodynamic components such as turning vanes, canards, and flaps are constructed using shorter fibres. The monocoque is constructed from longer, thicker fibres due to the physical need for it to be a strong, protective body. However, one thing to note is that for almost all of a car's external bodywork, the fibres are aligned continuously in a unidirectional manor.

Material Science of CFRP:

Composite structures are designed to have a specific quantity of fibres of specified length and width in a certain location and orientation, with a minimal amount of polymer to provide support to the fibres. The composites industry uses 'prepreg' as an intermediate product to achieve this. Prepreg is a broad type of aligned (unidirectional) or woven fibres, that is impregnated with polymer resin. A composite structure is formed by stacking layers of prepreg and curing under high temperature and pressure. Many of the CFRP components used in F1 consist of 'sandwich construction'. This involves taking prepreg sheets and separating them with thick, lightweight honeycomb shaped cores, which they are bonded to. This can significantly optimise the strength and stiffness of certain composite parts. Usually, this process is used for parts that are subjected to high forces, or parts that are not supposed to flex much [9]. This approach is often taken to produce high-strength and stiff parts of the car such as the monocoque. For aerodynamic parts, the prepreg is simply layered repetitively and bonded together.

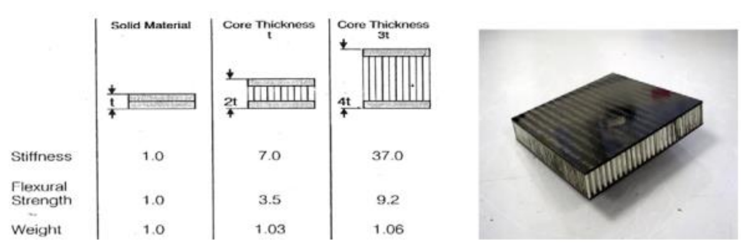


Figure 9: Diagram showing how the core thickness of carbon composite influences the stiffness and flexural strength.

Carbon fibres may be produced from three different precursor feedstocks; rayon, polyacrylonitrile (PAN) and pitch [9]. In the Formula 1 marketplace those produced from acrylic precursors (PAN) hold an overwhelming dominance. Polyacrylonitrile is a polymer derived from crude oil. Propylene and ammonia are formed, which then undergo another process to achieve polyacrylonitrile. In order to obtain carbon fibres, the PAN fibres undergo stabilisation. This is where the PAN fibres are heated to high heat treatment temperatures (HTT) in the absence of oxygen, so that the fibres are not ignited and burned. This removes any non-carbon atoms from the PAN fibres, aligning the carbon atoms, which in turn creates a stable molecular structure. A PAN based fibre will reach peak HTT at approximately 1500 °C which yields a Young's Modulus (E) of approximately 270 GPa [9]. PAN-based carbon fibres can be categorised by 3 different groups according to their Young's Modulus values. The most widely used group are those within the 1000 – 1400 °C range. These fibres have a diameter of around 7 µm and are known as 'standard modulus'. Across the Formula 1 grid, the most common grade of carbon fibre used for structures such as the front wing is 'intermediate modulus'. These fibres undergo a HHT process of 1400 – 1800 °C, giving a fibre diameter of 5 µm.

Fibre	Type	Fibre diameter (µm)	Approximate HTT (°C)	Tensile strength (MPa)	Tensile modulus (GPa)	Failure strain (%)	Density (g cm^{-3})
T300	Standard modulus	7	1000–1300	3530	230	1.5	1.79
T800	Intermediate modulus	5	1500	5490	294	1.9	1.81
T1000	Intermediate modulus	4.5	1500	6370	294	2.1	1.80
M46J	High modulus	4.4	2350	4210	436	1.0	1.84
M55J	Ultra-high modulus	4.4	2500	3780	540	0.7	1.93
M60	Ultra-high modulus	4.4	2600	3920	588	0.7	1.94

Figure 10: Table detailing the properties of different moduli of carbon fibres.

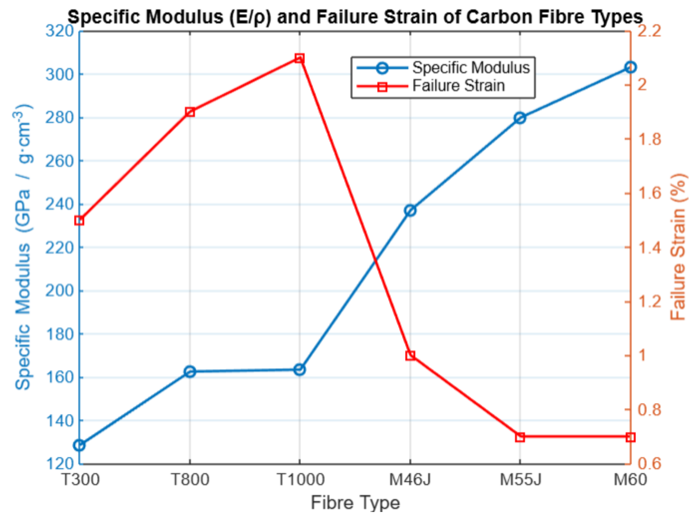
These fibres are woven into roves, forming cloths of carbon fibre which are then used to create prepreg. The prepreg uses a polymer resin to impregnate and support the fibres. In F1 the most common resin used is epoxy. Epoxy resins belong to the family of monomeric or oligomeric materials and have excellent mechanical properties, excellent electrical insulation properties, remarkable resistance to corrosion, excellent chemical resistance particularly to alkaline environments, and superior fatigue strength [10]. The prepreg is formed through a thermosetting layup method. Alongside the carbon fibres, the epoxy matrix also optimises the load bearing capacity of the finalised composite structure.

In order to have a reference value of the Young's modulus for the matrix material of the composites, the fundamental resonant frequency of pure epoxy was measured and a value of $E = 3.8 \pm 0.2$ GPa was obtained [11]. This value of E was found through testing carried out and documented in a research journal paper. We will use this value when analysing the mechanical and structural properties of CFRP.

The specific modulus of a material represents the stiffness to weight ratio, represented as:

$$Specific\ Modulus = \frac{E}{\rho}$$

I graphed the data from the above table using MATLAB. The failure strain is overlaid with the specific modulus of the different grades of carbon fibre. Ideally for a front wing structure, the wing should have a good strength to weight ratio, but also a high failure strain % so that it can flex by a certain amount under load. This is crucial in ensuring that the wing does not instantly fail when it is subjected to a critical load. The ability for the wing to slightly deform under intense loading conditions is an essential part of the flexi wing phenomenon. From the graph, the ideal modulus would be one that can withstand the maximum stresses experienced at high speed, have a flexing ability, and also be relatively lightweight. From our CFD simulation, the maximum pressure exerted on the wing at 300 kmph was approximately 4320 Pa. An intermediate modulus is more than capable of withstanding this stress, and they offer the best failure strain % compared to higher modulus carbon fibres. This graph supports the reason why F1 teams choose an intermediate modulus such as T800 or T1000 for aerodynamic parts such as the front wing.



An important quantity when analysing the carbon composite is the effective Young's Modulus of the material. This is a constant that represents the stress per unit strain of the entire composite. This is done by combining the moduli of the carbon and epoxy and relating them through their volume fractions (V_f and V_m) where 'f' denotes fibre and 'm' denotes the matrix material. The volume fraction of the carbon fibres and the epoxy resin obviously vary significantly depending on how many fibres are embedded in the structure relative to the epoxy that surrounds it. In order to perform analysis on the composite, highly quantitative data is required. To acquire this data, one would typically have to perform a series of tests and experiments in a lab. For the sake of time, and due to the lack of equipment available to carry this analysis out I used the data from Toray Composite Materials America Inc., one of the market leaders in carbon fibre production. They produce two types of intermediate modulus carbon fibre that likely resemble the carbon used by Formula 1 teams, T1000G and T800S. The difference between the two types of fibre can be seen in the above chart. Ideally, we would perform analysis of the T1000G fibres as they boast better performance qualities than the T800S using their product data sheets listed by Toray.

However, values for the volume fractions of T1000G were not given. Because of this, I used the data from T800S [12], which has very similar performance characteristics.

FIBER PROPERTIES

PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength	853 ksi	5,880 MPa	TY-030B-01
Tensile Modulus	42.7 Msi	294 GPa	TY-030B-01
Strain at Failure		2.0%	TY-030B-01
Density		1.80 g/cm³	TY-030B-02
Filament Diameter		5 µm	
Yield	12K	515 g/1000m	TY-030B-03
	24K	1,030 g /1000m	TY-030B-03

FUNCTIONAL PROPERTIES

PROPERTY	VALUE
CTE	-0.4 α ·10⁻⁶ /°C
Specific Heat	0.740 J/g ·°C
Thermal Conductivity	0.113 J/cm ·s·°C
Electric Resistivity	1.3 x 10⁻³ Ω·cm
Chemical Composition: Carbon	>96%
Na + K	<50 ppm

COMPOSITE PROPERTIES

PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength*	477 ksi	3,290 MPa	ASTM D-3039
Tensile Modulus*	24 Msi	163 GPa	ASTM D-3039
Tensile Strain		1.94%	ASTM D-3039
Compressive Strength*	216 ksi	1,490 MPa	SACMA SRM 1R-94
Flexural Strength*	247 ksi	1,700 MPa	ASTM D-790
Flexural Modulus*	21 Msi	145 GPa	ASTM D-790
ILSS	13 ksi	87.9 MPa	SACMA SRM 8R-94
In Plain Shear Strength	20 ksi	135 MPa	ASTM D-3518
90° Tensile Strength	11 ksi	79 MPa	ASTM D-3039

*Normalized to 60% fiber volume. Cured with #2592 epoxy at 130 °C.

Figure 11: Technical Data Sheet for T800S, sourced via the Toray Industries website.

We can see that from the bottom right corner of the data sheet, V_f is 60%. From this value, we can calculate the modulus of the carbon fibre composite. As discussed before, the values for E_f and E_m are 294 GPa and 3.8 GPa respectively.

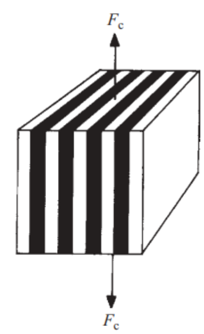


Figure 12: Directional loading.

Modulus for the composite where the fibres are orientated parallel to the direction of loading:

$$E_c = E_f V_f + E_m V_m = (294)(0.6) + (3.8)(0.4) = \mathbf{177.92\ GPa}$$

Modulus for the composite where the fibres are orientated perpendicular to the direction of loading:

$$E_c = \frac{E_f E_m}{E_m V_f + E_f V_m} = \frac{(294)(3.8)}{(3.8)(0.6) + (294)(0.4)} = \mathbf{9.32\ GPa}$$

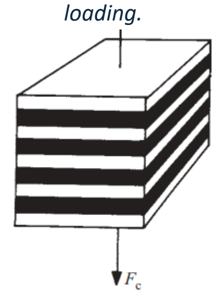


Figure 13: Perpendicular loading.

The above results demonstrate how the orientation of the fibres impact the load bearing capabilities of the composite. When the composite is loaded in the direction of the fibres, the material exhibits a much higher modulus compared to perpendicular loading. In the context of a wing's ability to flex, higher elastic modulus would mean that the material is stiffer and more capable of withstanding higher stresses.

Manufacturing Processes of CFRP in F1:

As we discussed already, the primary process for carbon fibre reinforced polymer production in Formula 1 is done by using thermosetting polymers. The carbon fibres are aligned in unidirectional continuous fashion in the form of rovings – collections of untwisted continuous strands. The rovings are woven into a thin, cloth structure. There are two types of weaves that are most common – plain weave (unidirectional diagonal pattern) and twill weave (crisscross pattern). Each weave offers different aesthetic and performance characteristics, which engineers can use to maximise the potential of the carbon fibre in various applications. Both types of weaves are seen on an F1 car, however most of the exposed carbon used in bodywork such as the front wing comes in the form of twill weave.

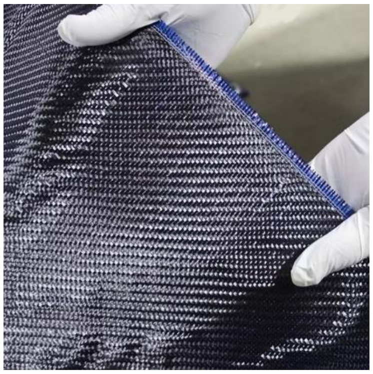


Figure 14: Carbon fibre prepreg with fibres arranged unidirectionally

The manufacturing process of carbon fibre reinforced polymers involves 4 complex main steps: spinning, stabilising, surfacing, and sizing. Firstly, the polyacrylonitrile plastic is spun into fibres. To do this, molten PAN undergoes extrusion, quenching, stretching in various ways, passed through a finishing oil, and cooling. The PAN fibres are then passed over hot rollers, turning the PAN fibres a black colour. The fibres are then heated to a chosen HHT, removing any non-carbon atoms. Once carbonised, the fibres have a surface that does not bond well with epoxies. Therefore, the fibres are oxidised, etched and roughened to improve their mechanical bonding properties. The fibres are then coated to protect them from damage during winding and weaving, also further improving adhesion to other materials. The coating is typically epoxy, polyester, or nylon. This coating ensures strong and reliable bonding between the fibres and the epoxy matrix. The newly formed carbon fibres are then loaded onto bobbins, which are then loaded into spinning machines to twist the fibres into rovings of various sizes [13 14 15]. The rovings are then woven into prepreg sheets by pulling them through an epoxy resin.

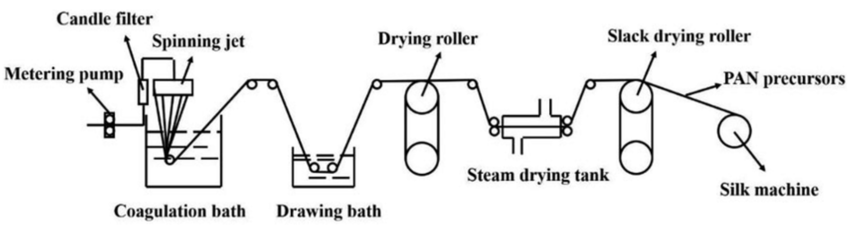


Figure 16: Production of PAN fibres.

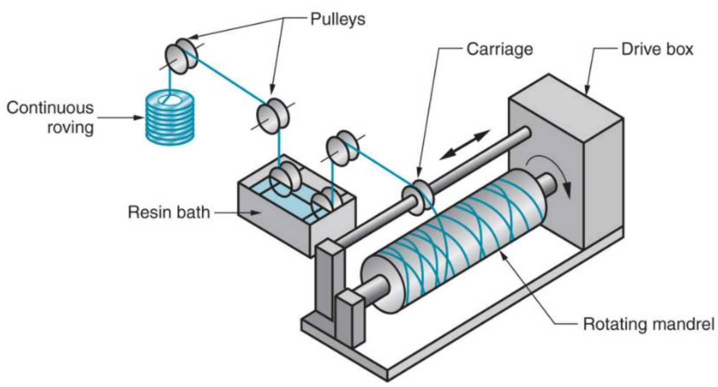


Figure 15: Weaving process of carbon fibre sheets from roving (source: 3B4 Module Notes)

Now that the prepreg sheets are formed, designers can use them to form parts. Parts are moulded inside an autoclave, a high-pressure, high-temperature oven-like device. Due to these high temperatures, the mould must not be susceptible to thermal expansion. Therefore, the mould is also usually made of carbon fibre. To produce the mould, a tooling prepreg is laminated on the pattern of choice. This gives the mould an initial thickness of 5 – 6 mm. This is initially cured at low temperatures (55 °C to 60 °C). Once this initial layer is cured, subsequent layers are put on top and cured at higher temperatures of up to 200 °C in a freestanding state.

Figure 17: CFRP Autoclave

The new mould is taken and treated with a release agent. A thin gel coating (epoxy) is then applied to the outside surface of the mould. When the epoxy has partially set, layers of carbon fibre cloth, coated in epoxy are built up. Most manufacturers will use a quasi-isotropic layup process. This involves layering the sheets so that the fibres are in different directional orientations, usually 0°/90° and -45°/45°. When the carbon fibres sheets are layered using this technique, they offer improved stiffness across their diagonal axis and significantly improved torsional stiffness [16]. Manufactures may alter the orientation of layers depending on the function of the part. For example, the front wing's carbon layers may not differentiate as much as that of the monocoque due to its requirements to flex a certain amount under loading. Between each instance of applying a new layer, the layers are rolled out to impregnate the fibres and remove any air particles. Once this process is complete, the structure is cured inside an autoclave at pressure of up to 6 bar (0.6 MPa) and temperatures between 120 °C and 180 °C. Manufacturing parts is a very laborious task with many steps.

For example, to manufacture a 1 m^2 part, the following steps would be taken:

1) Design verification: 2 hours.
2) Master pattern production: (a positive shape representing the ultimate component shape): 3 hours.
3) Carbon fibre mould lamination on the master pattern: 4 hours
4) Initial mould cure at 55 °C in an autoclave: 8 hours
5) Mold finishing and post-curing: 20 hours
6) Carbon fibre part lamination: 1 hour
7) Carbon part curing (total time in autoclave): 6 hours
8) Final part finishing and trimming: 1 hour
9) Delivery

Totalling approximately 45 hours [17].

Manufacturing Cost of CFRP:

The manufacturing process of a front wing is not cheap. The research required, and specialist equipment needed for manufacturing makes it a very challenging task. These complex shapes and labour hours make it difficult to estimate a true price. I tried reaching out to Crosby Composites, the UK's leading carbon fibre composite manufacturer, to find pricing. They are responsible for carbon fibre production for a lot of Formula 1 teams and high-performance automotive brands such as McLaren. They manufacture, front and rear wings, sidepods, halo fairings, steering wheels, seats, and many other composite parts for Formula 1 cars. I emailed them about pricing front wing manufacturing; however, I never got a response.

After this I reached out to Toray Composite Materials America Inc. I messaged Rory O'Kane, the Director of Product Management at Toray Advanced Composites, to try and get pricing on prepreg. He responded to my message with the following:

Hi Finn, nice to meet you virtually. I can give you a range to work with because as you are probably aware, even for epoxy resin, they are not all created equal, and quantity plays significant factor. If we consider high performance aero/F1 resin, then typically price range for T800 prepreg with approx. 60% FV is $60-90/sqm. I hope this helps and happy to connect you with our team in EU if you need samples. Good luck with your report. Ruairi. [18]

From this response, I will approximate the cost per square metre of prepreg as $80. From the 2024 FIA Formula 1 Technical Regulations, 'Inboard of Y=300, the forward-most two closed sections of the front wing must have a minimum thickness of 25mm when measured in the Z direction (vertical)' [2]. For thinner, aerodynamic components such as the endplates, the thickness would be minimised. The mainplane and elements centred about the nosecone are typically thicker so that they can withstand increased loading (50 mm). For the sake of calculation, we will use a thickness of 40 mm.

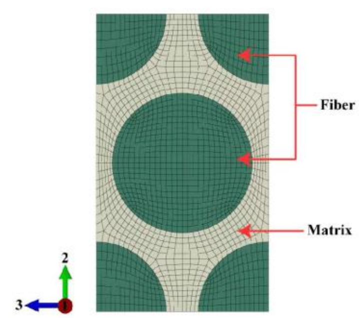


Figure 18: Matrix and fibre arrangement for CFRP composite.

Knowing the prepreg thickness is essential to calculate the component thickness. Data from Rock West Composites' website says that for Toray T800S, the prepreg thickness is 0.006 inches (0.1524 mm) [19]. This means that we can calculate an approximate cost to manufacture 1 m^2 of composite with thickness 40 mm and carbon volume fraction of 60%:

$$\frac{40}{0.1524} \times 0.6 = 157.48 \rightarrow 157 \text{ laminates} \times \$80 = \$12{,}560 \approx €11930 \text{ material cost}$$

According to ‘indeed.com’ and ‘TXM Recruit’, the hourly rate for a composite inspector/ technician is £26 - £34 per hour [20]. Taking an average of £30 per hour and 45 hours manufacturing time:

$$£30 \times 45 = £1350 \ \approx €1{,}620 \text{ labour cost}$$

$$\textbf{Total Manufacturing Cost for 1 m}^{\mathbf{2}}\text{: } €11{,}930 + €1{,}620 \ \approx €13{,}550$$

Of course, this is just an approximation, and real costs may differ significantly.

Carbon Fibre Composite End of Life Treatment:

As we have seen from watching Formula 1, most races involve a crash or at least some sort of damage, usually involving the front wing due to it being the front-most part of the car. Teams go through an immense amount of carbon fibre composite every season because of this. With F1 aiming to have a net-zero carbon footprint by 2030, the industry has been exploring a variety of recycling techniques such as mechanical shredding, fluidised bed thermolysis, and pyrolysis (depolymerisation). These techniques allow for new carbon composites to be created for a variety of different applications. In F1, many of the recycled pieces are used to create non-structural parts that do not undergo large stresses and loads. They may also be recycled to create other materials such as tennis rackets or other types of equipment in the form of short, discontinuously aligned fibres.

Mechanical recycling is done by attrition, compression, shearing and impact. This process involves recycling the fibres and matrices at once rather than using chemicals to decompose the composite into individual constituents. This process is followed by further grinding and milling, leading to a waste product of fine particles that are 10 – 50 mm. These particles are coarse and inconsistent in size, causing the carbon fibres to decrease in size and lose their high-strength properties. This new shredded material is not suitable for long carbon fibres that are capable of high load structural applications. Mainly, the recycled product is allocated to one of three categories: short fibres, fine powder, or coarse grains. Recycled short fibre is typically used in creating carbon composite with decreased performance quantities. When the short fibres are used to produce recycled carbon fibre composite, the flexural modulus increases by 15%, but the flexural strength decreases by 14%. [21]

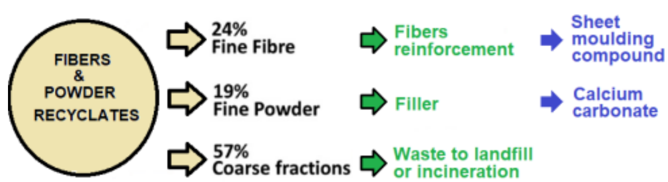


Figure 19: Mechanical recycling process of CFRP.

Another approach to recycling the carbon composite material is through fluidised bed thermolysis. This thermal method is done by decomposing the matrices through the use of a fluidised bed. Thermal methods like this usually produce fibres that are clean of contaminants and also convert the resin matrices into a fuel. However, this method requires a lot of energy, it degrades the fibre strength, and it also yields a toxic gas as a byproduct which is harmful to humans. This process uses a silica sand bed which is heated by hot air. The resin matrix is essentially burned off by the hot air at around 550 °C, however the carbon fibres recovered are reduced in strength by up to 25%. The diagram shown to the right displays the process for extracting carbon fibres via fluidised bed thermolysis. [21]

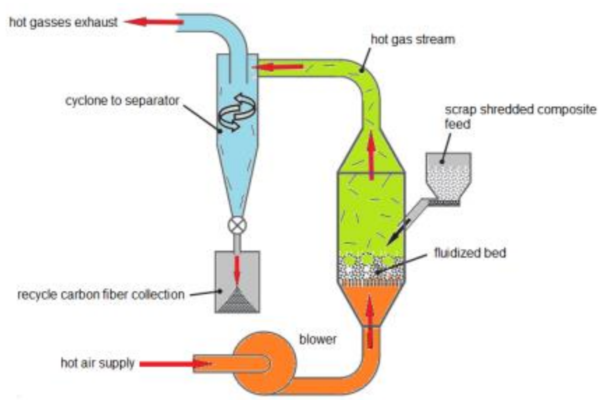


Figure 20: Fluidised bed thermolysis recycling process.

The last method I will mention is pyrolysis. Out of the 3 processes, this one yields carbon fibres that are most similar to the original samples used in constructing the composite. Pyrolysis works similarly to fluidised bed thermolysis, however the crushed composite goes through 2 combustion processes. Firstly, the coarse grains are passed through a pyrolysis reactor. This is a reactor that oxidises the composite at 500 °C – 600 °C for about 60 minutes. To further clean the remaining epoxy resin contaminants such as char, the fibres are passed through another combustion stage at a temperature below 500 °C. This process must be kept to below 600 °C to avoid damaging the fibres. [21]

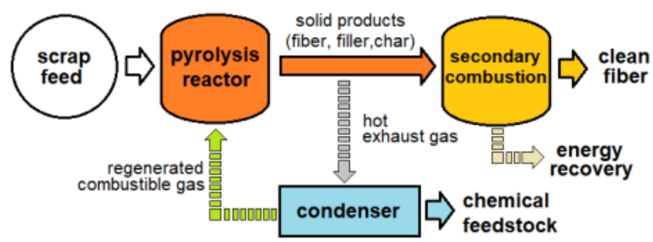
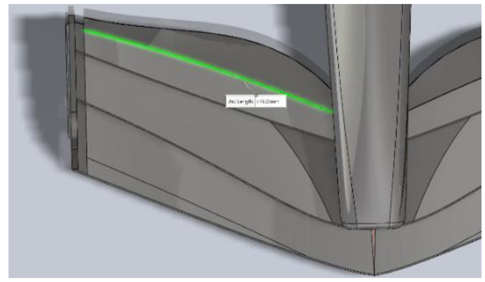


Figure 21: Pyrolysis recycling process.

In Formula 1 when a crash occurs, the teams will bring the car back into the pits, strip it back and analyse any damage caused to the chassis. Teams try to salvage as much material and components as possible. With regard to carbon fibre, this can be done by cutting parts off, replacing them, and recycling damaged parts using one of the recycling methods above.

Quantitative Analysis of CFRP Flexing Phenomenon:



We can use the results from the 2022 front wing CFD simulation in the following calculations. To measure the bending moment experienced by a portion of the wing, I chose to analyse the top flap. It is supported at one end by the nose cone and free at the other. Due to the irregular shape of the flap, a rectangular cross-sectional area of the flap was analysed. In the image to the right, the green line denotes the length (b) of the chosen flap. This flap appears to experience an average cross-sectional pressure of 2000 Pa across an area of 0.879 m^2.

Bending stress is given by the formula:

$$\sigma_{bending} = \frac{My}{I_{xx}} \; ; \quad where \quad I_{xx} = \frac{bd^3}{12} \quad and \quad M = Fd$$

$$I_{xx} = \frac{bd^3}{12} = \frac{(0.879)(0.043)^3}{12} = 0.00315\, m^4$$

$$M = (P \times A)d = (2000 \times 0.081)(0.879) = 142.4\, Nm$$

$$\sigma_{bending} = \frac{(142.4)(0.879)}{0.00315} = 39736.38\, Pa$$

To calculate the deflection at the tip of one of the flaps on the carbon composite wing, we can use the Euler-Bernoulli beam equation for a uniform distributed load.

$$\delta = \frac{\omega L^4}{8EI}$$

Where: δ = wing deflection; F = force applied at wing tip (N); L = wingspan (m); E = Young's modulus of carbon fibre composite in loading direction (Pa); I = second moment of inertia at the cross section (m^4) ; ω = distributed load (Nm).

First, we need to convert the uniformly distributed load from Pascals to Newton-metres:

$$\omega = P \times b = (2000)(0.879) = 1758\, N$$

As we discussed, CFRP is highly anisotropic, meaning that its load bearing capacity depends greatly on the fibre orientation. Typically, the carbon fibres for this portion of the wing are oriented in the direction of loading. From our earlier calculations, we know that E_c = 177.92 GPa for CFRP in the direction of loading.

$$\delta = \frac{(1758)(0.879)^4}{8(177.92 \times 10^9)(0.00315)} = 2.34 \times 10^{-7} = 0.234\, \mu m$$

This result suggests that there is very little deflection at this point of the wing. However, this result only demonstrates how a section of wing can flex based off of data generated from my CFD simulation and calculated CFRP elastic modulus. Typically, this top flap has a thick cross-section, making it more rigid but can be exposed to some slight deflection. Thinner aerodynamic components such as winglets and canards would be expected to flex by a greater amount. As per the FIA technical regulations, actual F1 car results will vary to this.

Failure Mechanics of Carbon Fibre Reinforced Polymers:

We can say that carbon fibre reinforced plastics fail due to Linear Elastic Fracture Mechanics (LEFM) rather than Elastic-Plastic Fracture Mechanics (EPFM). When reacting to a high magnitude force, the material exhibits a small amount of deflection. However, once the stress exceeds the critical yield stress of the CFRP, LEFM will cause sudden failure, resulting in a brittle failure rather than a gradual elastic one.

COMPOSITE PROPERTIES

PROPERTY	ENGLISH	METRIC	METHOD
Tensile Strength*	477 ksi	3,290 MPa	ASTM D-3039
Tensile Modulus*	24 Msi	163 GPa	ASTM D-3039
Tensile Strain		1.94%	ASTM D-3039
Compressive Strength*	216 ksi	1,490 MPa	SACMA SRM 1R-94
Flexural Strength*	247 ksi	1,700 MPa	ASTM D-790
Flexural Modulus*	21 Msi	145 GPa	ASTM D-790
ILSS	13 ksi	87.9 MPa	SACMA SRM 8R-94
In Plain Shear Strength	20 ksi	135 MPa	ASTM D-3518
90° Tensile Strength	11 ksi	79 MPa	ASTM D-3039

*Normalized to 60% fiber volume. Cured with #2592 epoxy at 130 °C.

Figure 22: T800S CFRP datasheet.

Using Toray's carbon fibre composite properties table, we can analyse the failure mechanics of CFRP when subjected to critical loading conditions. We can see that the flexural strength is 1700 MPa. This is the point where the material fails after significant flexion. Although, a front wing would never be subjected to such a high amount of stress in a race setting, we can use this to find the maximum deflection a point of the wing can withstand before failure. The following calculations are based on the part of the wing that we defined previously when analysing the flexing phenomenon.

$$\omega = P \times b = (1700 \times 10^{6})(0.879) = 1.49 \times 10^{9}\ N$$

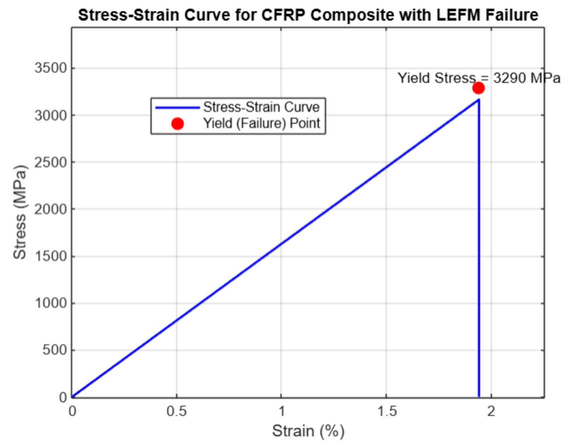
$$\delta = \frac{(1.49 \times 10^{9})(0.879)^{4}}{8(177.92 \times 10^{9})(0.00315)} = 0.19896\ m \sim 0.2\ m$$

From the above calculation, this portion of the wing deflects by approximately 20 cm before it fails in a brittle fashion.

Strain analysis can also be performed on this section of the wing using the formula. The table states that the maximum tensile strain of T800S CFRP is 2%. The total elongation due to tensile stress can be calculated through:

$$Elongation = Tensile\ Strain \times L = 0.02(0.879) = 0.01758\ m$$

In Formula 1, such failure would never occur due to aerodynamic loading. However, if such failure was possible during racing conditions, notice how only a small elongation and deflection occur before a totally catastrophic, brittle failure occurs.



Once this yield stress is hit, the material fails completely through LEFM. I generated the stress-strain curve on the right based on the data from Toray's carbon fibre composite datasheet using MATLAB. Once the critical tensile stress is reached, the curve immediately falls off to 0, indicating that the material has failed. This shows how brittle fracture occurs, rather than a plastic deformation like we would see in steel.

Recent Flexi Wing Controversies in Formula 1:

During the 2010s and even up until now in the 2024 Azerbaijan Gran Prix, wing flexion has always been a sensitive topic in Formula 1 aerodynamics. In the 2010 season, Red Bull Racing's RB6 front wing design was a topic of controversy. The wing appeared to flex downwards at high speeds, lowering the car's front end leading to boosted aerodynamic efficiency. This led to a debate surrounding front wing designs and their legality. The FIA had to step in and implement new regulations that limited the amount of deflection the wing could undergo. This involved reassessing the existing wing deflection tests that were in place. [22]

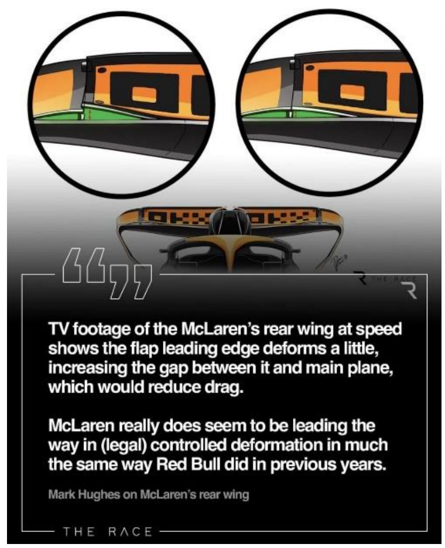


Figure 23: Statement issued regarding McLaren's flexing rear wing.

In recent times, we have seen further controversies surrounding wing deflection. Despite changes to regulations, teams are constantly finding new innovative loopholes to get around design limitations. This year, in the 2024 Azerbaijan Gran Prix, McLaren came under scrutiny for their rear wing design. Many other teams, and even F1 fans watching on TV, noticed that at high speeds, the McLaren rear wing exhibited noticeable flexing at high speeds on the straights. This was dubbed as the "mini-DRS" by many. This feature allowed the upper flap of the rear wing to open slightly under aerodynamic loading, which in turn reduced the cars' overall drag and increased their top speeds. Oscar Piastri went on to win the Azerbaijan Gran Prix, with the rear wing design playing a vital role in his success. Statements from drivers such as Sergio Perez saying, "It is clear that it violates the regulations", led to the FIA scrutinising McLaren's design after the race. However, McLaren proactively decided to adjust the rear wing after talks with the FIA. Bild, a reputable German media outlet said that McLaren sent a WhatsApp message to F1 journalists stating;

"While our rear wing in Baku complies with the regulations and passes all FIA bending tests, McLaren has proactively offered to make some minor adjustments to the wing following our discussions with the FIA. We expect the FIA to have similar discussions with other teams regarding the conformity of their rear wings". [23]

With regard to recent front wing controversy, McLaren and Mercedes have faced scrutiny from the FIA over their front wing designs. Ferrari and Red Bull team bosses both raised concerns about front wing deflection on their competitors' cars. However, after review, the FIA declared that the McLaren and Mercedes front wings were legal, and that they flexed to a degree that was compliant with regulations. Red Bull's team principal Christian Horner commented that the wording of certain technical regulations need to be reassessed, even if all front wings were deemed legal. The FIA's technical department stated that it carried out front wing checks at every race. They also said that the front wing had been a "challenging area" for years because aerodynamic loading patters varied between teams. The governing body said that it has the right to introduce new tests if irregularities are suspected, but there are no plans for anything in the short term. [24]

Conclusion:

Despite its controversy, the flexi wing phenomenon has become a key aspect of Formula 1 and enables the development of modern cars to push limits and maximise performance. Aerodynamic development has come a long way since the first introduction of a wing in motorsport. From Jim Hall's revolutionary first use of a wing device, to modern day Formula 1 cars finding innovative ways to 'flex' the rulebook so that aerodynamic efficiency can be maximised, some would say that aerodynamics play an even more vital role in Formula 1 than the powertrain unit. In previous instances, wing flexion has always been a topic of debate. Due to the high complexity of these aerodynamic systems, and deep understanding of materials science displayed by the teams on the grid, the likelihood of the flexi wing concept being revoked from Formula 1 is slim. It is an area of constant development and innovation, which sees engineers constantly pushing to break the boundaries of what is theoretically possible. These advanced aerodynamic technologies stand as the barometer of innovation for the automotive engineering industry as a whole, and influences sectors such as aerospace massively too. The world of materials science is also constantly developing and is currently on an upward trajectory.

The future of Formula 1 aerodynamics has a lot in store. No matter what regulations the governing bodies set, we will always see teams developing new and innovative ways to get around any restrictions put in place. The 'flexi wing' concept is a technological marvel that is the result of years of research and development across multiple areas of science. In my opinion, it is a device that is here to stay, which may sound like bad news to some. However, seeing that F1 is held as the pinnacle of racing, it should also represent the pinnacle of engineering and technological development.

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Figure References:

The figure references are given as hyperlinks below each figure.