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Stress Analysis and Dynamics

Design the structural support for a front
automotive wing for a new race series

University of Wales Trinity Saint David
Manufacturing Design & Technology - Level 5

Executive Summary

Following the instructions of Kelvin Lake, University of Wales Trinity Saint David, this report has calculated and analysed the design of a structural support for a front wing of a race car for an upcoming new race series. The structural section has been manufactured from steel tubing with a Young's Modulus of 210 Giga Pascal (GPa) and a circular cross section of gauge 2mm. The structure is holding the wing in all 6° of freedom.

Calculations have been made to determine the diameter of the steel tubing to ensure the car's front wing withstands the uniform load placed upon it during a race, while obeying regulations put in place by the FIA (Fédération Internationale de l'Automobile (French: International Automobile Foundation)), that the wing have a maximum deflection of 10mm. Research has been carried out to find "off the shelf" materials to help keep costs down, as well as alternative materials, with their advantages and disadvantages detailed. Different testing/calculating procedures were considered, along with their implications on budget.

This report documents the history and evolution of a race car's front wing and techniques that may improve the front wing in the future, although teams will be limited to the regulation put in place by the FIA.

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Terms of reference

This report has been prepared with the instructions from Kelvin Lake from University of Wales Trinity Saint David, dated July 2022.

Objectives of the report

To design the structural support for a front wing of a race car for an upcoming new race series.

Introduction

A structural support has been designed for the front wing of a race car. The structural section has been manufactured from steel tubing with a Young's Modulus of 210 Giga Pascal ($E=210\text{GPa}$) with a circular cross section of gauge 2mm. This structure is holding the wing in all 6° of freedom. The race regulations state that the end of wing deflection be "fixed". The minimum outside diameter of the structure was calculated using the principles of slope and deflections of beams theory. These calculations have been analysed, with possible limitations discussed.

The evolution of automotive racing front wings was reviewed and a supposition of how the front wing may evolve in the future produced. The materials and manufacturing processes of this evolution have been evaluated.

Possible experimental testing is discussed to determine how the calculations produced can be proven and interpreted.

Design

Due to regulations put in place, there are limitations to the dimensions of the race cars front wing. Figure 1 shows the regulation dimensions of a 2022 formula one race car put in place by the FIA (Fédération Internationale de l'Automobile (French: International Automobile Foundation)). These dimensions were used to carry out the wing's structural calculations.

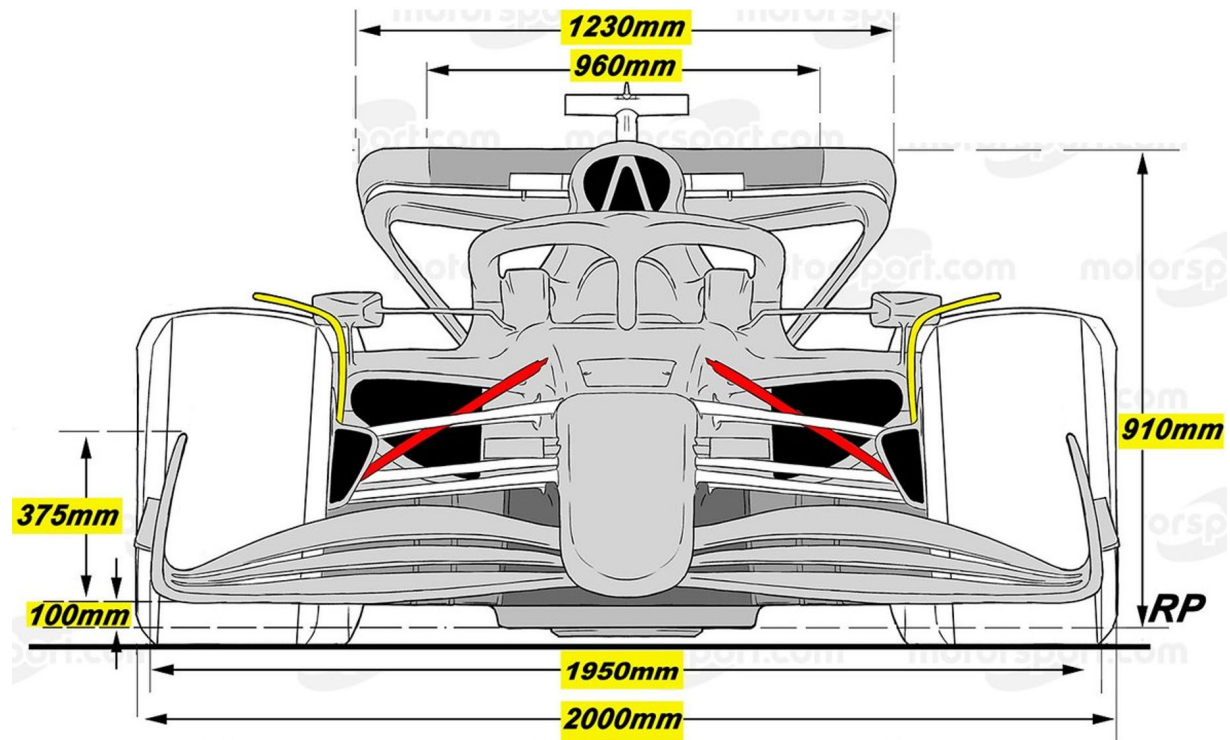


Figure 1 (Piola, 2022)

The length of a formula one car front wing is regulated to two meters (2000mm), therefore the length of the steel tubing required is determined as half this length to one metre (1000mm).

The aerodynamic load for the 2022 formula one race car is 740kg on the front wing and 1080kg on the rear wing (1820kg in total). As 740kg is the total load placed upon the whole of the front wing, then the load can be halved to 370kg (W) for each side of the wing structure. It was assumed that the aerodynamic loading on the front wing is uniform, to simplify the calculations. However, during real life conditions this is not the case, with the forces/load acting upon the front wing during race conditions varying across the wing, as illustrated in figure 6. (Anderson, 2022)(Katz, 2016)

Calculations

To calculate the size of the steel beam required, the second moment of area needs to be calculated. The below equation requires rearranging to solve for I .

$$Y_{max} = \frac{-WL^4}{8EI}$$

$$I = \frac{-WL^4}{8EY_{max}}$$

The race regulations state that the wing be stiff with a maximum deflection (Y_{max}) of 10mm.

Gary Anderson's journal in February 2022 stated that a formula one front wing has an aerodynamic load of 740kg, therefore, each structure will be under an aerodynamic load of 370kg (W).

Figure 1 shows the maximum front wing dimensions permitted within the 2022 FIA regulations. The maximum width is two meters, therefore the length (L) of the beam will be one metre.

The Youngs Modulus of Steel can have a value of between 190 – 210 Giga Pascal (GPa). This structure needs to have a Youngs Modulus (E) of 210GPa, therefore it is very stiff and will have a low deflection (Y_{max}). (Guide, 2021)

$$Y_{max} = 10\text{mm} (0.01\text{m})$$

$$W = 370\text{kg}$$

$$L = 1\text{m}$$

$$E = 210,000,000,000 \text{ Pa} (210 \text{ GPa})$$

$$I = \text{Second moment of area } m^4 \text{ (Unknown)}$$

$$I = \frac{-WL^4}{8EY_{max}}$$

$$I = \frac{370 \times 1^4}{8 \times 210000000000 \times 0.01}$$

$$I = 2.202 \times 10^{-8} \text{ m}^4$$

Having calculated the second moment of area and knowing that the circular cross-sectional gauge of the steel beam is required to be 2mm, a calculation can be made to determine the tubular structure required using the below equation.

$$i = \frac{\pi(D^4 - d^4)}{64}$$

For a beam with an outer diameter of 25mm (0.025m) and an inner diameter of 21mm (0.021m), the following calculations can be made.

$$i = \frac{\pi(0.025^4 - 0.021^4)}{64}$$

$$i = 9.63 \times 10^{-9} \text{ m}^4$$

The Value of i (9.63×10^{-9}) for a 25mm structure is lower than the required value previously calculated ($I = 2.202 \times 10^{-8}$) for the maximum deflection of 10mm.

To obtain a more accurate calculation and save many hours carrying out numerous calculations, an excel spreadsheet was produced (figure 2).

I has been calculated by inserting the $I = \frac{-WL^4}{8EY_{max}}$ formula and i has been calculated by inserting the $i = \frac{\pi(D^4 - d^4)}{64}$ formula into the figure 2 spreadsheet.

The spreadsheet proves the above calculations.

Diameter (D) mm	Diameter (D) m	diameter (d) m	i
1	0.001	0.0006	4.27312E-14
2	0.002	0.0007	7.73713E-13
3	0.003	0.0008	3.95648E-12
4	0.004	0.0009	1.25358E-11
5	0.005	0.001	3.06345E-11
6	0.006	0.002	6.284E-11
7	0.007	0.003	1.13898E-10
8	0.008	0.004	1.8852E-10
9	0.009	0.005	2.91421E-10
10	0.01	0.006	4.27312E-10
11	0.011	0.007	6.00908E-10
12	0.012	0.008	8.1692E-10
13	0.013	0.009	1.08006E-09
14	0.014	0.01	1.39505E-09
15	0.015	0.011	1.76659E-09
16	0.016	0.012	2.1994E-09
17	0.017	0.013	2.69819E-09
18	0.018	0.014	3.26768E-09
19	0.019	0.015	3.91258E-09
20	0.02	0.016	4.63759E-09
21	0.021	0.017	5.44744E-09
22	0.022	0.018	6.34684E-09
23	0.023	0.019	7.3405E-09
24	0.024	0.02	8.43313E-09
25	0.025	0.021	9.62944E-09
26	0.026	0.022	1.09342E-08
27	0.027	0.023	1.2352E-08
28	0.028	0.024	1.38876E-08
29	0.029	0.025	1.55458E-08
30	0.03	0.026	1.73313E-08
31	0.031	0.027	1.92487E-08
32	0.032	0.028	2.13028E-08
33	0.033	0.029	2.34982E-08
34	0.034	0.03	2.58398E-08
35	0.035	0.031	2.83322E-08
36	0.036	0.032	3.09801E-08
37	0.037	0.033	3.37883E-08
38	0.038	0.034	3.67614E-08
39	0.039	0.035	3.99042E-08
40	0.04	0.036	4.32214E-08

Y_{max}	0.01
W	370
L	1
E	2.1E+11

I	2.2E-08
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$$Y_{max} = \frac{-WL^4}{8EI}$$

$$I = \frac{-WL^4}{8EY_{max}}$$

$$i = \frac{\pi(D^4 - d^4)}{64}$$

Figure 2 - Spreadsheet of calculations

Analysis

When looking/using figure 2, it can be determined that a 33mm beam would be required as the 32mm falls slightly short. If a standard sized beam could be used, it would keep costs down and make replacement and repairs quick and easy. On investigation, Metals4U.co.uk sell a 38.1mm x 2mm Mild Steel Seamless Tube in a two-metre length for £78.46 +VAT. This is an off the shelf product and this length could be used for both wings, either side of the nose. (Metals4u.co.uk, 2022)

On further investigation, it was found that Pipe Dream Fittings (PipeDreamFittings.com) stocked a 33.7MM Outside Diameter steel tube at a length of one metre for £5.37 +VAT. This sized beam is a closer match to the calculation for I ($2.20238E-08 \text{ m}^4$) at $2.51217E-08 \text{ m}^4$ than the Metals4U alternative at 38.1mm with an I value of $3.70688E-08 \text{ m}^4$ (figure 3) and could be overkill, while adding additional unwanted weight to the race car. Even though two beams would be required, this is again an off the shelf product and would be extremely cost effective given the delicacy of these wings and the fact they can be damaged very easily. (Pipedreamfittings.com, 2022)

Diameter (D) mm	Diameter (D) m	diameter (d) m	i
38.1	0.0381	0.0341	3.7068E-08
Diameter (D) mm	Diameter (D) m	diameter (d) m	i
33.7	0.0337	0.0297	2.51217E-08

Y_{max}	0.01
I	2.20238E-08

Figure 3 - Off the shelf materials I values

Alternative Principles and Methodologies

Due to weight and strength being important factors in the construction of a race car, alternative materials can be introduced to improve the performance of the race car. When looking at the materials properties chart in figure 4, metals and alloys have a high Youngs Modulus (stiffness) but can also be the densest (heaviest) material on the chart.

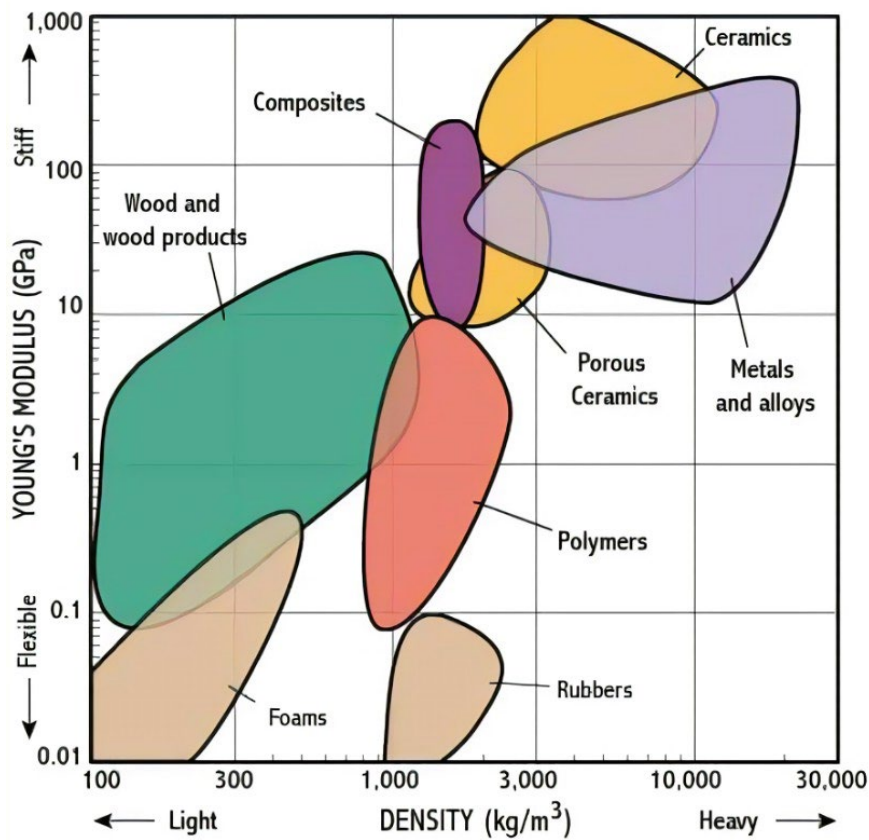


Figure 4 (McCarthy, 2009)

As an alternative to metal/alloy, a composite material could be used. Composites such as carbon fibre have high stiffness, high tensile strength, low weight, and a high chemical resistance. Carbon fibre is generally ten times stronger and half the weight of steel. Carbon fibre has become the go to material for race teams due to these properties, but this material does come at a cost. Steel is generally a more cost-effective material compared to carbon fibre, but the carbon fibre manufacturing process, skilled labour, and material all contribute to its costs. Producing carbon fibre is a very precise and time-consuming manufacturing process. The majority of formula one teams have an extremely large budget so even though carbon fibre has a higher cost, it is stronger, lighter, and built to last much longer than its steel counterpart. (Zhang, 2019; Zoltek, 2021)

When BBC's Richard Hammond teamed up with Chris Jones (Materials Engineer) at an engineering materials test centre for BBC Engineering connections – Formula One, a torque test was carried out on two drive shafts, a steel drive shaft and a carbon fibre drive shaft. The first drive shaft to be tested was made from steel. The steel drive shaft failed (twisted) on reaching 1376 Nm of Torque. The carbon fibre drive shaft withstood a greater torque and failed (twisted) at 4728 Nm of Torque.

Even though the carbon fibre drive shaft was able to support a much higher load than the steel drive shaft, it was supporting specifically designed/directed loads. Carbon fibre does not perform well with high loads applied in a small specific area, for example, a bullet hitting a sheet of carbon fibre, and it does not perform well if loaded counter to the design. Also, carbon fibre is much more brittle than steel. Both steel and carbon fibre can be superior to the other depending on the application. (Hammond, 2022)

An alternative method to testing and calculating the effects of aerodynamic loads placed upon the front wing would be the use of a wind tunnel. A race cars aerodynamics play a much larger role than just downforce, the air that travels over the body of the car can be used to its advantage. This air can be used to aid the cars performance in other ways, such as guiding air into the engines ventilation pods and assisting with the cooling of the brakes. Figure 5 shows how air can travel over a race car and how it can be redirected to assist with other performance features. During this wind tunnel testing, the car can be tweaked and modified by its designers to obtain perfection. Although, this technology does come at a cost, but with many formula one teams having such vast budgets, many teams have invested in their own wind tunnels for testing. (Motorward, 2013)

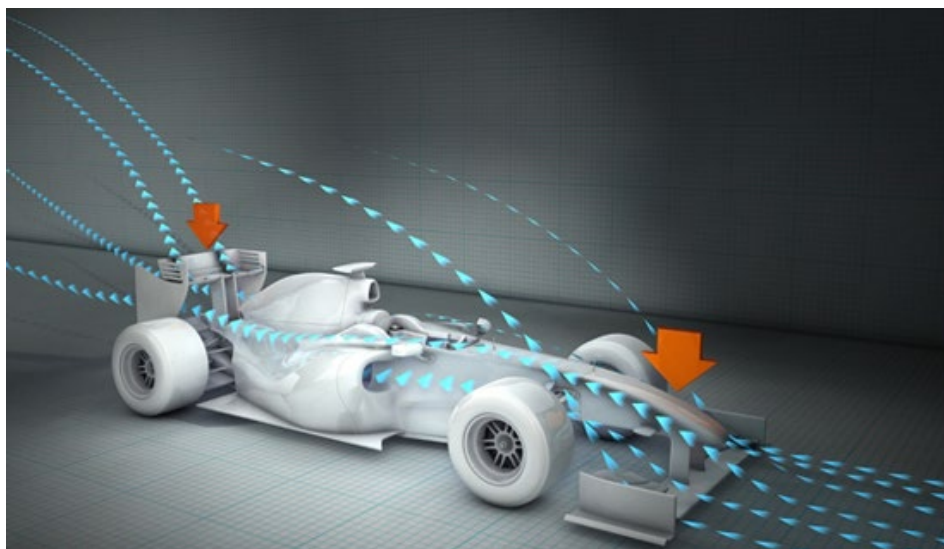


Figure 5 Formula One car in a wind tunnel (Motorward, 2013)

Prototype

Depending on the race teams' budget, there is several possible options to materials and testing a prototype, that can prove the calculations provided.

Limited Budget Option

A prototype can be manufactured from an off the shelf steel product. It is proposed that two 33.7mm steel tubes be purchased from Pipe Dream Fittings and used to secure the race cars front wing for testing. If a strain gauge/monitor was to be fitted to the front wing, the car could be driven around a track at race speeds with the deflection monitored. Adjustments could be made to the wing and endplates after each lap. This would be very monotonous and time consuming.

Large Budget Option

As many formula one teams have very large budgets, a carbon fibre tube could be manufactured to specific dimensions, but at a high cost. This material would be stronger than steel and a lot lighter, providing a distinct advantage over steel. The car could be tested using a wind tunnel and strain gauge/monitor to make adjustments in real time.

Computational Method

Another method of testing is computational fluid dynamic (CFD). This method can be affordable and have a positive impact due to computational power. When used in the design and testing of the automotive industry, a large body of information can be provided by the "solution." This data could be reviewed, investigated, and analysed after the testing is concluded. A virtual design could be created before a structure/race car has even been built and could provide information on real world aerodynamic loads. While this method could appear to be advantageous, computational tools are not perfect and require knowledgeable aerodynamicists to run and interpret the results.

As figure 6 demonstrates, the load acting upon the front wing is not uniform and testing would be required. The purple colour on the outer of the front wing highlights higher loads, with the blue demonstrating lesser loads.

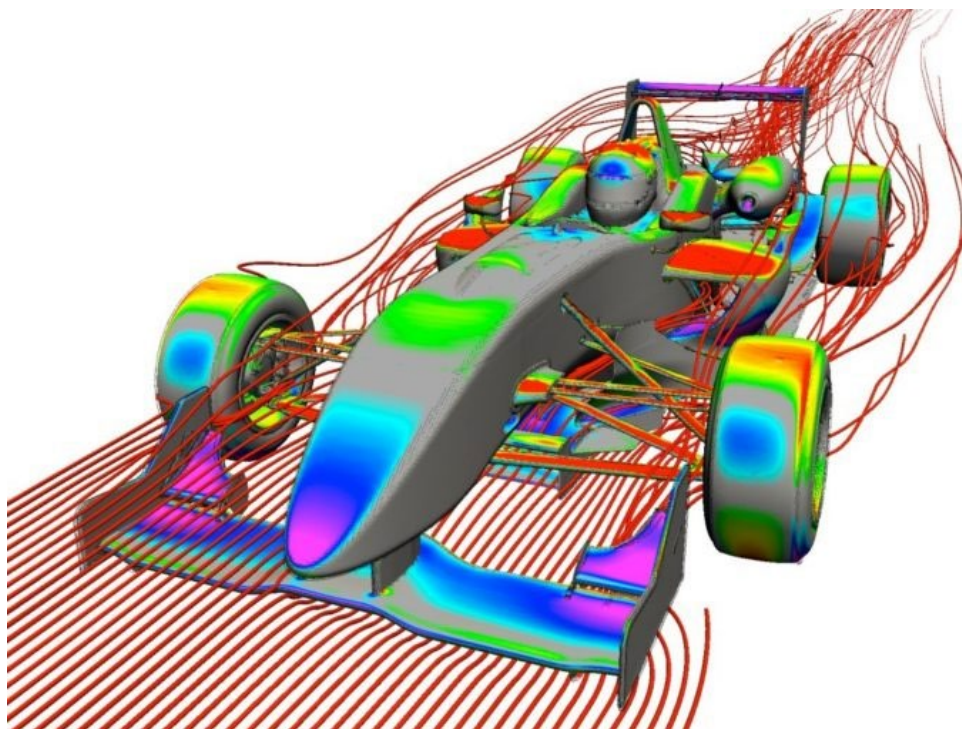


Figure 6 (Katz, 2016)

The Evolution of the Automotive Racing Front Wing

Graham Hill's Lotus was the first to utilise the front wing at Monaco in 1968. This started with an amazingly simple single element (figure 7) and has developed into the extremely complex front wing seen today (figure 8).(Oggioni, 2019)(Komentar, 2022)



Figure 7 (Oggioni, 2019)



Figure 8 (Komentar, 2022)

Figure 9 shows how a parallel airflow travels over a non-symmetric profile, producing an airstream of low-pressure high speed and high-pressure low speed areas, creating different pressures which have different effects upon the wing. With forces generally acting in the direction of the low-pressure areas, this wing would create a lifting effect (Oggioni, 2019).

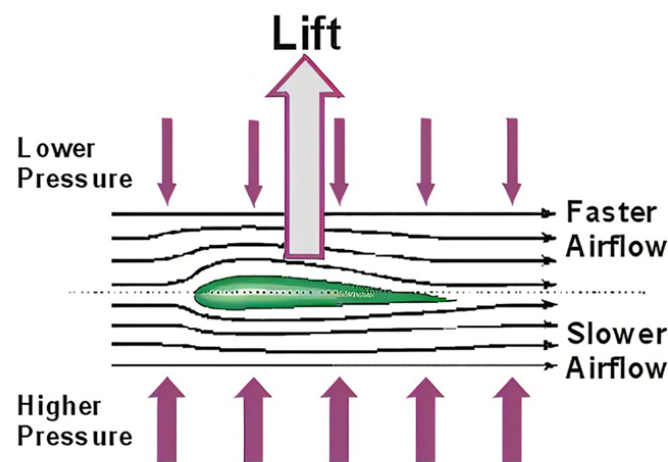
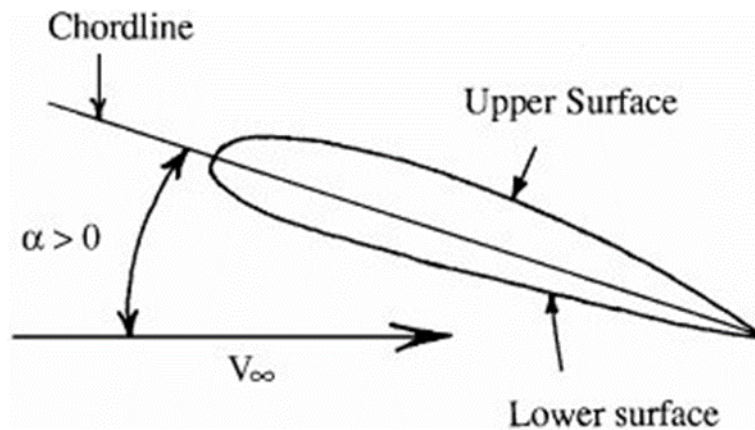
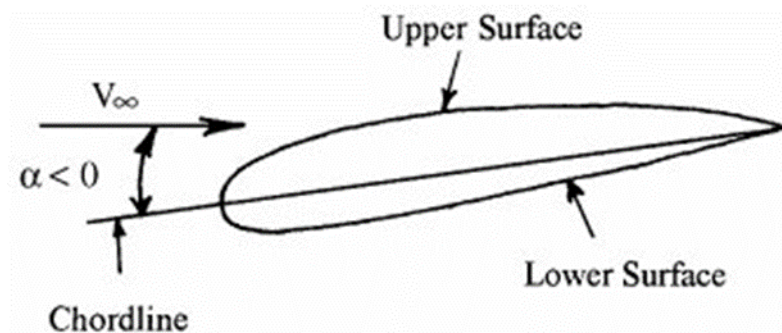


Figure 9 (Mechanical360, 2017)

Figure 9 demonstrated how beneficial this shape can be for aeronautical applications by creating lift, in particularly for an aircraft, but in terms of racing, lift is bad. Car constructor Jim Hall came up with the brilliant idea of inverting the wing to a negative angle of attack (figure 10), therefore producing negative lift, also known as downforce (Oggioni, 2019). Even though this idea changed the concept and look of a racing wing, it also came with its difficulties. There are fine margins with this application and if the wing was to become too low, it could increase the chance of the vortices collapsing and creating turbulent air flow, this could ruin the entire airflow for the rest of the car (Beck, 2013).



a) Airfoil at positive angle of attack



b) Airfoil at negative angle of attack

Figure 10 (Oggioni, 2019)

To help reduce this turbulent air, designers introduced end plates to the wings in an attempt to reduce the drag created. Another example of this can be found on the wings of aeroplanes. The Wright Brothers curved the edges of their aircrafts rectangular wings, based on their wind tunnel results. On modern aircrafts, the ends of the wings are curled up and referred to as Winglets. Using figure 11 as an example, the introduction of winglets, reduces the vortices at the end of a wing and helps reduce the drag component. At the NASA Dryden Flight Research Centre, flight tests have proven that there was a 6.5% reduction in the fuel used by a Boeing 707 aircraft when using winglets (Hall, 2021). The same principle was used when introducing the end plate to the racing cars front wing and therefore why so many teams put in so much effort to the development of the wing's endplate design (Just, 2010). Figure 12 is an example of a modern front wing looking more plane like, with a reduced 3 element wing and simple wide end plates.

Winglets

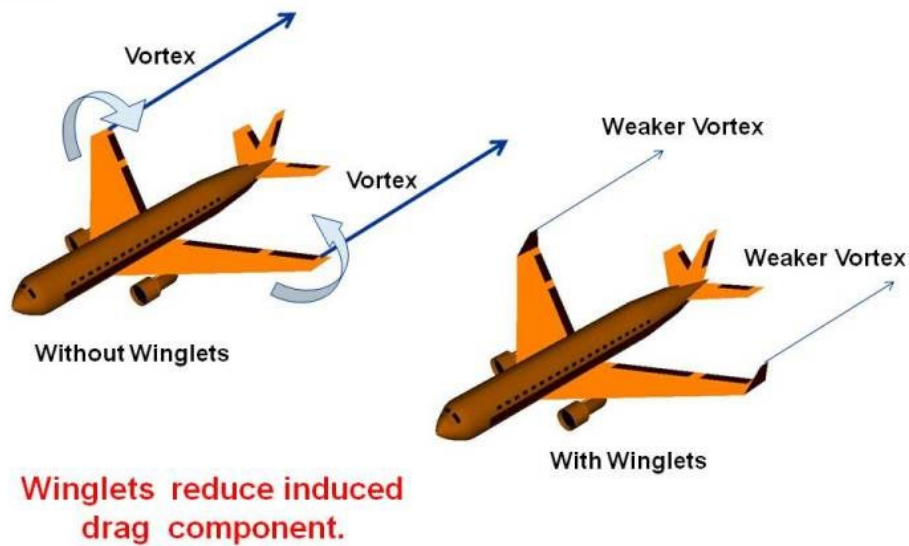
www.nasa.gov

Figure 11 (Hall, 2021)



Figure 12 (Mitchell, 2019)

The future of the front wing will continue to develop in design, to reduce drag and create more downforce, but this will be bound by the regulations put in place by racing governing bodies. The new regulations have allowed teams to further develop their cars front wings, allowing cars to travel closer behind each without compromising the chasing cars dynamics and therefore more exciting spectacle for the fans of this complex but beautiful sport.

Conclusion

This report has determined the minimum size of tubing structure for a front wing of a race car. For the front wing to withstand 370kg of uniformly distributed load with a maximum deflection of 10 mm and a Young's modulus of 210GPa, it was calculated that a steel tubing of 33mm would be required.

These calculations have been carried out assuming the load is uniform, but during real world race conditions, this load would not be uniform. To obtain a more accurate real-world calculation, on track testing could be carried out with the wing being monitored during high straight-line speeds and cornering. Further testing could be carried out using a wind tunnel, although the use of a wind tunnel comes at a high cost. As previously stated, many formula one teams have very large budgets and a wind tunnel test would be carried out by all teams, with many of the teams owning their own wind tunnels. This can lead to teams making the same adjustments to their front wings and exceptionally fine margins between lap times, hence the importance of getting these calculations right.

These calculations were carried out for a steel structure, but for a race car, weight can have a dramatic effect on speed and lap times. If cost was not a factor, then an alternative material of carbon fibre could be used. Carbon fibre can be manufactured to be stronger and lighter in weight.

As manufacturing methods and the development of new materials improve, the front wing of a race car will continue to change shape and become more aerodynamic, but this will always be bound by the regulations put in place by racing governing bodies.

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