

DESIGNING THE STRUCTURAL SUPPORT FOR A FRONT AUTOMOTIVE WING FOR A NEW RACE SERIES

ACMA 5010: Stress Analysis and Dynamics

Andrew Burgess (2115107)
2115107@student.uwtsd.ac.uk

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Introduction

The purpose of this report is to record the findings of an investigation into structural parameters supporting the front wing of a race car due to compete in a new race series. The investigation will establish the minimum diameter support to be used in the manufacture of the new wing design. According to racing regulations, the maximum deflection of the wing is set to 10mm.

The investigation will be completed through mathematical methods. As with any calculation purporting tangible outcomes, assumptions and approximations are made to allow the calculations to be completed quickly and to a satisfactory approximation of real-world values. Therefore, alternative methods to those used in this investigation will be considered.

This report will also consider the design and manufacture of wings historically. As methods and principles change and become more refined, the features of front wings have evolved. The methods used to manufacture wings have changed and contribute to the forces they are exposed to and their subsequent reactions.

To validate the selection of support in the wing, a prototype is to be produced for testing. This report aims to advise on the method that should be used and how the results of the experiment should be interpreted. Using this information, it would be possible to establish the accuracy of the calculations.

Problem

Assumptions

For this solution, the front wing will be considered a cantilever beam. The end of the wing supported by the nose cone is considered fixed, there will be no deflection at the base of the wing. This is unrealistic as the suspension of the car will absorb some downforce, reducing the deflection on the wing. The length of the wing is based off the 2022 Formula One front wing as specified by the FIA (Racecar Engineering, 2022). According to Anderson (2022) the front wing of a modern formula car can withstand 750kg of downforce, including its own mass. This is represented as a UDL, which is unlikely to be the case on the physical wing due to its complex profile and changing surroundings.

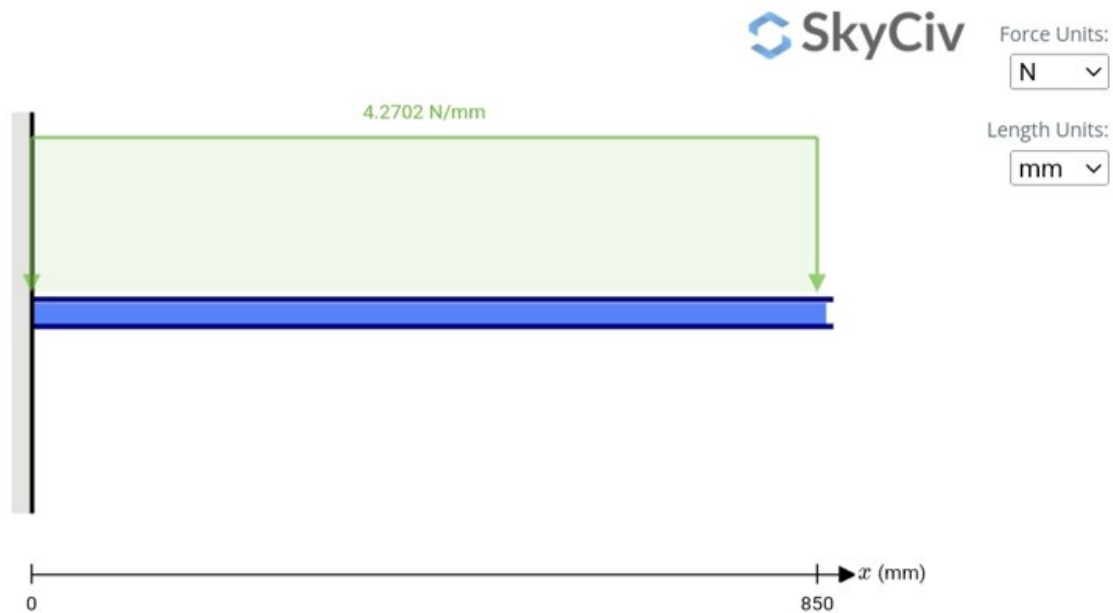


Figure 1: Representation of the front wing

The material of the tube is steel with a Young's modulus of 210GPa and a nominal 2mm wall thickness. A tolerance is normally applied to any dimension and will influence its actual deflection. The thickness is assumed to be consistent across the entire tube. Discrepancies in the thickness would offset the deflection of the wing. Similarly, the structure of the steel tube is assumed to be homogeneous, the young's modulus being equal across the entire tube. This negates irregularities like seams and welds from manufacturing. Welds create variations in the crystal structure at and around the site of the weld which can vary according to their composition and size, both of which influence the mechanical properties of the weld (Davies, 1993). This solution assumes the downforce produced by the flow over the wing is distributed evenly along its length, which allows the moment of inertia to be calculated using a UDL. CFD analysis would provide more accurate results of the downforce but maybe considered unnecessary if the tube size is limited to standard sizes that can be procured.

Solution

If the maximum displacement of the wing is 10mm(0.01m) at its furthest point from the centre of the nose, the formula for the maximum displacement is used to find the required moment of inertia of the tube.

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

$$0.01 = \frac{-(4.2702 \times 10^3)(0.85^4)}{8(210 \times 10^9)I}$$

$$0.01 = \frac{-2229.071}{1.68 \times 10^{12}I}$$

$$(1.68 \times 10^{12})(0.01)I = -2229.071$$

$$I = \frac{-2229.071}{(1.68 \times 10^{12})(0.01)}$$

$$I = \frac{-2229.071}{1.68 \times 10^{10}}$$

$$I \text{ (moment of inertia)} = 1.3268 \times 10^{-7} m^4$$

The formula for the moment of inertia of a tube was transposed to find its diameter.

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

$$1.3268 \times 10^{-7} = \frac{\pi}{64} (D^4 - d^4)$$

$$\frac{(1.3268 \times 10^{-7})(64)}{\pi} = (D^4 - d^4)$$

$$2.703 \times 10^{-6} = (D^4 - d^4)$$

Solving this equation required multiple operations to complete. In this case the value for the diameter was found using a spreadsheet calculating the diameters within 0,001mm (1µm). This method quicker and provided sufficient accuracy. Figure 2 shows the results and dimensions of the tube, with the closest value highlighted. The results were checked by finding the value of d and is found in Appendix A. This gives an error of 0.012%, which is acceptable and shows this method has a suitable level of accuracy.

Moment Of Inertia (m ⁴)	Outer Diameter (m)	Internal Diameter (m)	Outer Diameter (mm)	Internal Diameter (mm)
1.32634E-07	0.05725	0.05325	57.250	53.250
1.32641E-07	0.057251	0.053251	57.251	53.251
1.32648E-07	0.057252	0.053252	57.252	53.252
1.32656E-07	0.057253	0.053253	57.253	53.253
1.32663E-07	0.057254	0.053254	57.254	53.254
1.3267E-07	0.057255	0.053255	57.255	53.255
1.32677E-07	0.057256	0.053256	57.256	53.256
1.32684E-07	0.057257	0.053257	57.257	53.257
1.32692E-07	0.057258	0.053258	57.258	53.258
1.32699E-07	0.057259	0.053259	57.259	53.259
1.32706E-07	0.05726	0.05326	57.260	53.260
1.32713E-07	0.057261	0.053261	57.261	53.261
1.3272E-07	0.057262	0.053262	57.262	53.262
1.32728E-07	0.057263	0.053263	57.263	53.263
1.32735E-07	0.057264	0.053264	57.264	53.264

Figure 2: Table of values closest to the calculated moment of inertia

The exact outer diameter was found to be 57.257mm and the internal diameter was 53.257mm. Once the diameter of the tube was determined, the closest commercially available size of tubing, above the calculated diameter, was selected. Selecting a tube diameter below this value could, in theory, create a deflection exceeding the 10mm limit.

Steel Express (2022) offers imperial tube with a nominal diameter 2 3/8" x 14SWG (60,3 x 2.03mm) whilst the European Committee for Standardization (2016) specifies the closest standard size over the calculated diameter as 60 x 2mm; having a larger moment of inertia of 1.5342×10^{-7} and a deflection of 8.6mm, complying with racing regulations. Given the options, the nominally smallest tube size would be selected to minimise mass.

Verification

When setting out to test a new front wing design, a number of tests can be completed in order to gain satisfactory results and approval of a concept. With the size of the tube established earlier within this report, it is necessary to confirm the results using additional methods. According to Katz (2006), there are many methods that can be used to test the aerodynamic effectiveness of a particular feature. These include Computational methods and physical testing. Within the computational methods there is Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA). For physical testing, tests include wind tunnel testing and road testing. All of these tests can vary in the results that are obtained and the costs they incur.

Before a prototype is designed and manufactured, the wing design should be tested using computational methods like CFD and FEA. The purpose of CFD is to analyse the effect of a body's surface on its surrounding fluid medium (Anderson, Jr., 1995). Given the equipment is available to use, it is an inexpensive option when compared to other methods like wind tunnels. Using models that are developed through Computer Aided Design (CAD), it can be continuously remodelled to determine the correct aerodynamic effect that is required before creating prototypes and performing more expensive and challenging physical tests (Tucker, 2016). As for the results, the downforce can be calculated using the CFD software by selecting the correct regions, without altering the results as seen with physical methods (Anderson, Jr., 1995).

Following the CFD analysis to determine the downforce and its distribution, the effects of this action can be established using Finite Element Analysis (FEA). FEA is used to provide an insight into how a body will respond to a changing environment using a set of equations known as the mathematical model (Koutromanos, et al., 2018). By dividing a body into multiple cells, the software is able to calculate the forces and movement of the body when work is applied. This would be used to establish the reaction of the wing when the vehicle is cornering and accelerating, as the varying loads caused by these actions will impact not only the deflection but also its longevity. Analysing how the wing reacts to differing stresses can help to establish if it is safe to conduct physical testing, reducing the risk of injury and damage to an expensive vehicle and prototype wing. Motor sporting groups like Formula 1 using a similar wing setup can spend approximately \$300,000 per assembly, emphasising the use of cheaper methods like CFD and FEA for testing rather than physical components (F1Chronicle, 2020).

Once the design has been verified, there are a number of options for physical testing on the prototype wing. One option is to use a wind tunnel, which effectively forces air over a component or assembly of choice as it would when the vehicle is moving (Wittwer, et al., 2013). This is safer than testing on the track immediately as any failure or excessive deflection can only damage the equipment or the prototype. Yet this process is expensive due to the energy, labour and maintenance required can cost up to £300,000 for some full-scale tests (Tucker, 2016). Scaling the model requires higher wind speeds to account for the difference in area and requires a wind tunnel with more power and subsequently demand a higher price (Wittwer, et al., 2013). The results of these tests can be viewed in real time using pressure sensors to measure the downforce in areas of interest. Realistically, a wind tunnel would be avoided unless the design has been optimised extensively using digital methods.



Figure 3: An intricate scale model of a F1 car to be tested in a wind tunnel. Every detail is recreated to provide the most accurate results, at a price (Stuart, 2021).

Aero-rakes are another tool used to measure flow over areas of the car as it is used on the track (Smedley, 2019). The aero-rake is attached the vehicle behind a feature of interest and the car is driven along the track, allowing the aero-rake to collect data on the flow and how it changes at different speeds and directions (William-Smith, 2022). Software converts this data into an image or video that is used to measure the deflection of the front wing as it travels. Although it cannot measure the downforce on its own, aero-rakes can establish the deflection of the wing from the change in flow, which is required in order to comply with racing regulations (Smedley, 2019). The Kiel probes used on Aero-rakes are normally accurate to $\pm 0.01\text{mm}$ of actual values (William-Smith, 2022).



Figure 4: The Kiel Probes secured to the scaffolding forming the aero-rake. This setup is being used to measure the air flow over the wheels and linkage (Smedley, 2019).

Design

A front wing is a device that is used within automotive racing which exerts more friction on the front tyres (Katz, 2006). All front wings are designed to provide downforce that effectively pushes the vehicle towards the ground, compensating the lift that is experienced by the vehicle as it travels at high speed (Szudarek & Piechna, 2021). According to Mokhtar and Lane (2008) the downforce that is generated by the front wing is used to provide better traction during acceleration and allows the car to corner at higher speeds. Castro and Zeeshan (2020) adds the front wing aids braking to the increased traction afforded to the tyres.

The front wing works off the principle of the Aerofoil used in winged aircraft, manipulating air above and below the profile to apply pressure on either surface (Mokhtar & Lane, 2008). As air profile, the air passing over either side of the aerofoil travels at different velocities. Air travelling a greater distance over the wing will do so at a higher velocity, whilst air travelling a shorter distance will do so at a lower velocity. Using Bernoulli's principle, a higher velocity will result in lower pressure over the wing and the opposite for a lower velocity (Mokhtar & Lane, 2008). The pressure difference creates an upwards or downwards force that, in the case of a car, can increase or decrease traction through the wheels. The magnitude and direction of this force is influenced by the shape of the aerofoil and its angle of attack (Katz, 2006). Shown in Figure 3 aerofoils can be both symmetric and cambered to alter the velocity of air over particular areas of the wing (Katz, 2006). Whilst aircraft would use a similar profile to those in Figure 3, the front wing of a race car would use inverse cambered aerofoils. This way, the velocity of the air is highest underneath the wing and lowest above the wing (Castro & Zeeshan, 2020). This has the opposite effect of lift and forces the front of the car downwards towards the ground.

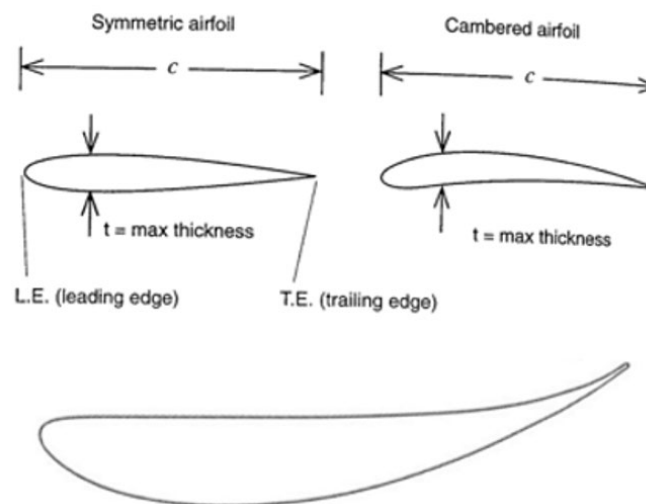


Figure 5: The varying shapes of an aerofoil.

According to Oggioni (2019), the front wing was first used within the 1968 Monaco Grand Prix. It was attached to a Lotus 49B, a simple design compared to modern front wings. The design was composed of an inverse aerofoil fixed to either side of the nose. The angle of attack allowed provided downforce but added significant drag. (Mokhtar & Lane, 2008) adds that further development of front wings proved that the distance between the wing and the ground can increase the downforce the wing further (Agathangelou and Gascoyne, 1998). As wings developed, they incorporated more aerofoils or elements which increased downforce but also drag. The profile of these elements vary to account for this drag and vary in shape (palanivendhan, Vengatesan, Dutta and Jain, 2020). In recent years, the end plate has been used to direct air flow over the wing and prevent spilling over but maintaining the cantilever shape. In the future, front wings will become simpler as other aerodynamic design features like rear wings and floor plates are relied on moreso (Red Bull Racing, 2022).



Figure 6: The first front wings (top) resembled simple inverted aerofoils (Oggioni, 2019) whilst modern front wings (bottom) utilise multiple wing elements and additional features like end plates (Stuart, 2021).

Construction

When designing a front wing for racing, there are numerous requirements. Functionally, a front wing must generate sufficient downforce for the vehicle to be competitive. Thus, the wing must have the correct profile, using a single or multiple aerofoil elements. Along with the shape of the wing, it must be lightweight and have sufficient strength to withstand the total downforce it generates (Agathangelou & Gascoyne, 1998).

Front wings fitted to racing cars are constructed similarly to wings used on aircraft. Fulfilling the requirement for low weight, wings are constructed through a series of supports, or ribs, in the shape of the aerofoil. These ribs are intended to support the skin of the wing and provide the desired shape to the wing element (Katz, 2006). Ribs are normally constructed from sheet metals like aluminium or from thicker polymers (Oggioni, 2019). The distribution and density of the ribs will dictate the magnitude of deformation across the wing and its overall mass. Increasing the number of ribs increases the mass of the wing, but also its stiffness. The opposite is true by decreasing the number of ribs. To counter this trend, cut-outs are introduced between the mounting holes for the longitudinal spars. The shape and size of the cut-outs may vary depending on the forces that are expected to be applied on the rib itself. Low stress applications can use rectangular or triangular cut-outs (Castro & Zeeshan, 2020).

Connecting the ribs and further supporting the skin is the spars. These are longitudinal pieces that connect to the ribs at different positions along the wing. Larger wings have spars positioned around its perimeter whilst others will secure the spars at the centre of each rib. The number of spars vary according to the deflection and the force exerted on the wing (Katz, 2006). The shape of the spar is dependent on the total deflection of the wing that is expected/required. The 2022 Formula one front wing using extruded I-sections that minimising deflection due to its shape. Other front wing designs use a tubular support which runs the length of the wing (Castro & Zeeshan, 2020). Spars are subjected to shear forces where they interface to the ribs, so the material is selected according to its Young's modulus, yield strength, density, stiffness and toughness. The materials used include steel, magnesium, titanium and aluminium alloys. The cheaper of these are the steel and aluminium alloys, which are more likely to be used on a tighter budget. Yet, titanium and magnesium alloys offer the highest yield strength-to-weight ratio (Castro & Zeeshan, 2020).

The skin of the wing consists of mostly carbon or aramid fibre composites. The skin is expected to be strong and lightweight and consists of braided structures constructed in alternating directions to provide strength across multiple axis (Agathangelou & Gascoyne, 1998). The fibre structure is made rigid using a thermoset polymer like epoxy or Polyetherketone (PEK).

Older front wings used steel structures to support the frame through the ribs and spars. A sheet metal skin was wrapped around the frame, consisting of steel or aluminium (Oggioni, 2019). With development into wing's structure and the increasingly technical nature of racing, greater efforts were made to make the wing stronger, more effective and reduce mass (Agathangelou & Gascoyne, 1998).

Conclusion

To conclude, the calculations provided the size of the tube required within an acceptable level of accuracy, giving the minimum diameter of the tube. Yet, these calculations, do not account for factors like manufacturing tolerances and the car's suspension, not providing a realistic insight into the forces and conditions that the wing is to encounter during physical testing. For that reason, the assumptions are not realistic and negates a number of factors that would skew the results.

Hence, investigation is required to verify these results and to ensure that the wing is capable of withstanding all conditions it is expected to perform. By verifying the design through digital methods reduces the cost and risk of damage or injury through oversight in the design phase.

This does not make physical testing redundant but used later in testing to prove its function when subjected to real-world conditions like acceleration and cornering. The construction and processes used to create the prototype wing must perform effectively for testing but maintain a low cost to allow further development.

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Appendices

Appendix A – Check of solution to find the diameter of the tube

The tube consists of two unknown diameters separated by a known wall thickness of 2mm (0.002m).

If,

$$D - d = 4 \times 10^{-3} \quad (\text{Total wall thickness})$$

$$(1) \quad D = 4 \times 10^{-3} + d$$

Then,

$$(2) \quad D^4 - d^4 = 2.703 \times 10^{-6} \quad (\text{Moment of Inertia})$$

Where,

$D = \text{Outer diameter}$

$d = \text{Inner diameter}$

Substituting Eq1 into Eq2,

$$(4) \quad (4 \times 10^{-3} + d)^4 - d^4 = 2.703 \times 10^{-6}$$

Expanding $(4 \times 10^{-3} + d)^4$,

$$(4 \times 10^{-3} + d)^4 = (4 \times 10^{-3} + d)^2(4 \times 10^{-3} + d)^2$$

Expanding $(4 \times 10^{-3} + d)^2$,

$$(4 \times 10^{-3} + d)^2 = (4 \times 10^{-3} + d)(4 \times 10^{-3} + d) = 1.6 \times 10^{-5} + 8 \times 10^{-3}d + d^2$$

$$\therefore (4 \times 10^{-3} + d)^4 = (d^2 + 8 \times 10^{-3}d + 1.6 \times 10^{-5})(d^2 + 8 \times 10^{-3}d + 1.6 \times 10^{-5})$$

Arranging the two quadratic equations in the form of,

$$(ax^2 + bx + c)(dx^2 + ex + f) = (ad)x^4 + (ae + bd)x^3 + (af + be + cd)x^2 + (bf + ce)x + cf$$

Where,

$$a = 1,$$

$$b = 8 \times 10^{-3},$$

$$c = 1.6 \times 10^{-5},$$

$$d = 1,$$

$$e = 8 \times 10^{-3},$$

$$f = 1.6 \times 10^{-5}$$

$$(d^2 + 8 \times 10^{-3}d + 1.6 \times 10^{-5})^2 = (1)(1)d^4 + [(1)(8 \times 10^{-3}) + (1)(8 \times 10^{-3})]d^3 + [(1)(1.6 \times 10^{-5}) + (8 \times 10^{-3})(8 \times 10^{-3}) + (1)(1.6 \times 10^{-5})]d^2 + [(8 \times 10^{-3})(1.6 \times 10^{-5}) + (8 \times 10^{-3})(1.6 \times 10^{-5})]d + (1.6 \times 10^{-5})(1.6 \times 10^{-5})$$

$$(5) \quad (d^2 + 8 \times 10^{-3}d + 1.6 \times 10^{-5})^2 = d^4 + 16 \times 10^{-3}d^3 + 9.6 \times 10^{-5}d^2 + 2.56 \times 10^{-7}d + 2.56 \times 10^{-10}$$

Substituting (5) into (4),

$$d^4 + 16 \times 10^{-3}d^3 + 9.6 \times 10^{-5}d^2 + 2.56 \times 10^{-7}d + 2.56 \times 10^{-10} - d^4 = 2.703 \times 10^{-6}$$

$$0.016d^3 + 0.000096d^2 + 2.56 \times 10^{-7}d + 2.56 \times 10^{-10} = 2.703 \times 10^{-6}$$

$$0.016d^3 + 0.000096d^2 + 2.56 \times 10^{-7}d - 2.7027 \times 10^{-6} = 0$$

Given that this is a cubic equation, an online tool was used to find all solutions (Calculator Soup, 2022).

Where,

$$a = 0.016,$$

$$b = 0.000096,$$

$$c = 2.56 \times 10^{-7},$$

$$d = -2.7027 \times 10^{-6}$$

This gave the following answer,

$$d = 0.05325m$$

$$d = 53.25mm$$

Using d to find the value of D,

$$D = 4 \times 10^{-3} + 53.25 \times 10^{-3}$$

$$D = 57.25 \times 10^{-3}m$$

$$D = 57.25mm$$