

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

Stress Analysis and Dynamics



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Ioan Davies
2115169

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Calculating Minimum Outside Diameter of Structural Support

MINIMUM MOMENT OF INERTIA TO LIMIT DEFLECTION:

$$D = \frac{WL^4}{8EI} \quad \therefore I = \frac{L^4 W}{8ED}$$

L, LENGTH = 0.9m

E, YOUNGS MODULUS = $210 \times 10^9 \text{ N/m}^2$

W, FORCE = 60 N/m

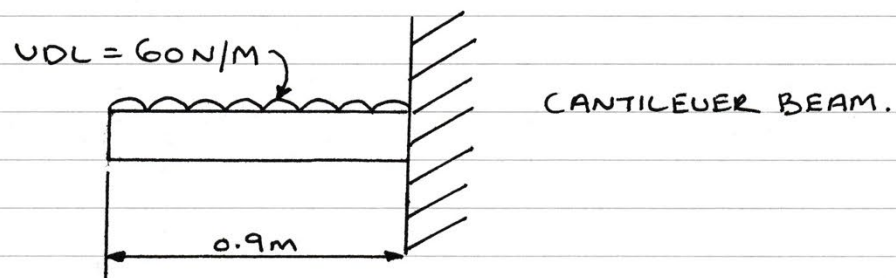
D, MAXIMUM DEFLECTION = 10mm = 0.01m

$$I = \frac{0.9^4 \times 60}{8 \times 210 \times 10^9 \times 0.01} = 2.3432 \times 10^{-9} \text{ m}^4$$

$$D = \frac{60 \times 0.9^4}{8 \times 210 \times 10^9 \times 2.3432 \times 10^{-9}} = 0.01 \text{ m (MAX)}$$

$$EI = 210 \times 10^9 \times 2.3432 \times 10^{-9}$$

$$EI = 492.072 \text{ N/m}^2$$



$$y_{\max} = \frac{-WL^4}{8EI} = \frac{-60 \times 0.9^4}{8 \times 492.072} = -0.01 \text{ m} = 10 \text{ mm}$$

$$\left(\frac{dy}{dx}\right)_{\max} = \frac{WL^3}{6EI} = \frac{60 \times 0.9^3}{6 \times 492.072} = 0.0148 \text{ (no units)}$$

ADDING FACTOR OF SAFETY TO MOMENT OF INERTIA:

$$FOS = 1.5$$

$$I = \frac{2.3432 \times 10^{-9}}{1.5}$$

$$= 1.5621 \times 10^{-9}$$

$$= 2.3432 \times 10^{-9} + 1.5621 \times 10^{-9}$$

$$I = 3.9053 \times 10^{-9} \text{ m}^4$$

SELECTING APPROPRIATE HOLLOW TUBE SECTION SIZE:

$$3.9053 \times 10^{-9} \text{ m}^4 = 0.39053 \text{ cm}^4$$

USING SECOND MOMENT OF AREA FOR CIRCULAR HOLLOW SECTIONS STANDARD SIZES, FOR STANDARD TABLE IN BS EN 10210-2.

STANDARD SIZE HOLLOW SECTION DIAMETER = 21.3 mm

THICKNESS = 2.3 mm

SECOND MOMENTS OF INERTIA = 0.677 cm⁴

SMALLER THICKNESS REQUIRED TO MEET REQUIREMENTS:

$$I = \frac{\pi(D^4 - d^4)}{64 \times 10^4} = \frac{\pi(19^4 - 15^4)}{64 \times 10^4}$$

$$I = 0.3912 \text{ cm}^4 = 3.912 \times 10^{-9} \text{ m}^4$$

∴ D, OUTSIDE DIAMETER = 19 mm (NOT STANDARD).

INSIDE DIAMETER = 15 mm

WALL THICKNESS = 2 mm.

FIND NEW DEFLECTION VALUE USING NEW VALUE FOR, I .

$$EI = 210 \times 10^9 \times 3.912 \times 10^{-9} \\ = 821.52 \text{ N/m}^2$$

$$y_{\max} = \frac{-WL^4}{8EI} = \frac{-60 \times 0.9^4}{8 \times 821.52} = -5.9898 \times 10^{-3} \text{ m}$$

$$y_{\max} = -0.006 \text{ m or } -6 \text{ mm}$$

$$\left(\frac{dy}{dx}\right)_{\max} = \frac{WL^3}{6EI} = \frac{60 \times 0.9^3}{6 \times 821.52} = 0.0089 \text{ (no unit)}$$

$\therefore$ OUTSIDE DIAMETER OF 19mm FOR A HOLLOW CIRCULAR SECTION BEAM, WITH A THICKNESS OF 2mm AND LENGTH OF 0.9m WILL LIMIT THE DEFLECTION TO 0.6mm, INCLUDING A FACTOR OF SAFETY OF 1.5, WHEN A MAXIMUM FORCE OF 60N/m IS UNIFORMLY DISTRIBUTED ACROSS THE BEAM.

Limitations and Assumptions of Calculations

To carry out the slope and deflection calculations on the front wing support, I was required to make a few assumptions. Firstly, I assumed that the front wing support acts as a cantilever beam. This is a beam with one end projecting beyond the point of support fixed in all six degrees of freedom, with a free end. The beam is free to move in a vertical plane when a vertical load is applied (Rosato & Rosato, 2003). Another assumption made was a uniformly distributed load is applied to the beam, meaning that a force is distributed over the entirety of the known length. To imitate the potential practical load exhibited on the front wing through downforce, which is the difference in air pressure that pushes the wing into the ground (Formula Trinity, 2021).

The value for the front wing length was established using details from the Formula One 2022 technical regulations. Which states that the front wing must not exceed 1000mm either side of the centreline of the car, including the end plates (Fédération Internationale de l'Automobile, 2022). Therefore, a front wing beam length of 900mm was used in the calculations removing a potential length of 100mm for the end plates. The FIA regulations also state that the wing must not deflect more than 3mm when subjected to 0.06kN/m of force. Although the deflection is much smaller in this scenario it can be used as a standard for the beam's deflection behaviour. A factor of safety was also incorporated into the final calculations to produce a result that would ensure the maximum deflection value is never exceeded. And allows room for overloading of force or difference in component sizes due to tolerances. As this will directly affect the components second moments of area. I also assumed that the cross-section of the beam is constant between the support and the free end.

There are also limitations to the slope and deflection of beam theory calculations firstly, the beams fixed position to the car body. Although the beam will be fixed at one end it will never be fully secure in all six degrees of freedom so there will be a small margin of error. However, this helps to simplify the calculations. It is also difficult to account for variable or complex beam sections for example, a tapered section towards the centre. This provides difficulties calculating the second moment of inertia for the section as it would not be a constant. This method can also become complicated when the unknown displacements have high values, which can become confusing and lead to calculation errors.

One alternative method that could have been used instead of deflection of beam theory is FEA analysis. Finite element analysis (FEA) is a software method of predicting how a product reacts to real world forces and physical effects such as vibration, heat, and fluid flow (Autodesk, 2022). The main purpose of FEA is to determine if a component will fracture or wear out when used in the application it was intended for. (Zhuming, 2019) suggests that FEA is a task used for design analysis and applies external forces to a model in different potential scenarios to optimise the design solution. Therefore, it could be used to determine the front wing beams optimal material thickness for a required load. However, this method is much more expensive and time consuming to produce results.

Another alternative involves conducting mechanical testing on potential front wing beams. One appropriate method is a tensile test. A tensile test is a destructive test process that is used to provide information about the tensile strength, yield strength and ductility of metallic material (Jawaid, Thariq, & Saba, 2019). Tensile testing measures the forces required to break a material and how much the test piece elongates before breaking. Multiple steel tube sections of various outside diameters could be tested using the tensile test process to determine the maximum load the tube is capable of withstanding before elongation begins also known as plastic deformation. This is known as the yield point and yield strength of a material.

Automotive Front Wings

The front wings of sports cars are highly important in both generating downforce helping the car to remain in firm grip with the track and regulating airflow around and behind the front tyres helping to reduce drag (Patridge, 2021). Most modern Formula 1 cars use a front wing design consisting of multiple elements arranged one behind the other known as aerofoil sections. As explained by (Gorostidi, Lecourt, Castro, & Maigler, 2020) when more downforce is required simply increasing the aerofoil angle section will help to a certain point, taking airflow from below and pushing it up and over its surface. However, if the curvature becomes too extreme the air will begin to leave the front wing as chaotic flow which instead begins to reduce downforce. (Warrier, 2021) states that the aerofoil should create a smooth flow of air around the lower surface and pulling up at the trailing edge, this air flow pulling up in turn pulls the aerofoil down creating downforce. To avoid this scenario and increase downforce the aerofoil can be split into multiple sections arranged behind each other with airflow gaps maintaining a smooth airflow around each section.



Figure 1: This image shows the front wing of the Ferrari SF90 2019 Formula 1 competition car. This is a common example of modern multiple element automotive front wing (Hughes, 2019).

A much different front wing design can be found with Formula E cars, with a simple and robust design favoured over the complex multiple element front wing of Formula 1 cars. The main reason for this is to provide further strength to the front wing which is required to withstand large amounts of contact (Smith, 2022) due to the nature of the sport on narrow and tight tracks. The aesthetics of the front wing are also more important in the Formula E sport as mentioned by (Dow, 2022). With key features of the car designed to look significantly different to other automotive sports series. Although the Formula E front wing produces less downforce than the Formula 1 design due to its flat plane sections, this makes minimal difference as all drivers in the competition must use the same car.



Figure 2: This image shows the front wing of the Jaguar 3rd Generation Formula E competition car. This design has a unique double tier robust structural design (Attwood, 2022).

Automotive front wings have continuously developed from their introduction into the Formula 1 racing series in 1968 with Lotus. The front wing was introduced to prevent positive lift by inverting an air foil section used in aeronautics to produce negative lift also known as downforce (Oggioni, 2019). The downforce produced by the wing provides further traction to the road and allows the car to travel faster without the risk of lift, especially when cornering. The original front wings consisted simply of a simple aerofoil section in a negative angle of attack as shown in figure 3.



Figure 3: First automotive front wing introduced onto Graham Hills Lotus, Monaco 1968 (Oggioni, 2019).

Over the surface of a front wing the two areas of low and high pressure will meet at the wing tips and flow leakage will occur, whereby the high-pressure air migrates to low pressure air. This results in a wing circulation that trails downstream and forms a key component of wake turbulence (Zhang, Zerihan, Ruhrmann, & Deviese, 2002). At the core of these vortices a region of low pressure is present. Therefore, during the 1970s endplates were introduced to the front wings to help delay the flow which allows a higher angle of attack for the aerofoil and in result increased downforce and diverts airflow around the front tyres reducing drag.



Figure 4: Ferrari 1975 Formula 1 competition car with newly implemented endplates on the front wing design (Affat, 2019).

Further development of automotive front wings changed little until 1984 except for reduction in ground clearance that was used to further increase downforce. In 1984 McLaren introduced a new front wing design that implements a simple two-layer multi-element wing. As previously discussed, the multi-element wing uses stepped aerofoils to provide an even higher angle of attack without blocking airflow and increasing drag on the wing (Castro & A. Rana, 2020). More complex multi-element front wing designs have since developed following the introduction of computational fluid dynamics (CFD) since the 2010s as seen in Figure 1.

With further advances in CFD and CAD technology front wing designs will become more complex and detailed to direct the air flow more efficiently and accurately further reducing drag and increasing downforce. This will also allow the cars to travel faster and perform at a higher level. However, Formula 1 have begun to implement regulations since 2019 that limits the amount of aerofoil

element to five and banned turning devices around the endplates to decrease the wake width and promote overtaking opportunities (Fédération Internationale de l'Automobile, 2022). Therefore, a focus will be taken towards downforce compared to redirecting airflow around the front tyres.

Manufacturing of Automotive Wings

Automotive wings are constructed with carbon fibre reinforced polymer composite (CFRP). A carbon fibre reinforced polymer composite is a material that's structure consists of continuous carbon fibres within an epoxy matrix. The fibres carry any mechanical loads applied to the material and the epoxy matrix distributes the load to the fibres and binds them together. This produces a material with a high strength to weight ratio that is also ductile (F. Ashby, 2013). The high strength to weight ratio is very important for front wings of Formula 1 cars for example. As the component must withstand strong downforces but be as light weight as possible to ensure car performance is not affected. The bracket that connects the wing to the central nose of the car may also be CNC machined from a low-density Aluminium material to provide the component with more rigidity if necessary.

The main manufacturing methods used in producing CFRP components are vacuum infusion, filament winding and continuous processing and wet spray-up or lay-up moulding. However, due to the complicated shapes of automotive wings such as the modern multi element aerofoils shown in Figure 1, the wet lay-up or spray-up moulding process is most used (Patil, 2021). Wet lay-up is a skilled manual process that involves carefully layering woven or chopped carbon fabric into a mould of the desired shape, the matrix polymer resin is then applied and spread with a brush or roller. This is then left to cure at an ambient temperature for several hours to fully harden. It is also common for a gelcoat to be applied to the mould before the carbon fabric is placed onto it to provide a good surface finish to the top surface (CompositesUK, 2022).

Furthermore, wet spray-up involves feeding the resin matrix through a spray nozzle mixed with a catalyst, the carbon fibre is then fed through a bobbin and chopped into the resin stream as it is sprayed onto the mould surface. An adequate layer is built up around the mould before being left to cure. Although this method is quicker it can lead to a low fibre volume and randomly orientated fibres so is best suited to prototype manufacture of automotive wings. The multiple components of a modern multi element formula 1 wing for example are then assembled by structural resin adhesives that slot together in mating joints. They may also be assembled using fasteners where necessary.

Building and Testing of Prototype

If a prototype was to be produced to verify my calculations, I would firstly produce a CAD model of the beam (structural support for front wing) using the dimensions as previously calculated. Following this FEA software could then be used to apply the specified load, determine fixed locations and a free end. The FEA breaks down the object into thousands of finite elements and computes mathematical equations to predict the behaviour of each element (Autodesk, 2022). These elements are then added together to predict a behaviour for the entire object. If the calculations are accurate then the results of the FEA will be very similar, with close attention to the slope and deflection values. Ensuring that deflection does not exceed 10mm. Although the results of FEA are not 100% accurate, they can be interpreted as an accurate prediction of the components behaviour for comparison against the manual calculations. However, if the results of the FEA are not comparable to the calculations or the deflection values are far greater than 10mm then the calculations must be thoroughly checked along with the input values of the FEA software.

Following accurate FEA results that compare to the manual calculations a prototype of the beam can then be manufactured according to dimensions stated in the calculations and the material specified in the brief. A standard sized steel tubing section could then be purchased and cut to the required

length alternatively, stock material can be machined to a non-standard diameter hollow tube section. However, this option will be unnecessarily costly for a prototype and take much more time to produce.

The prototype beam can then be tested using a simple experimental testing method to measure the deflection of the beam and compare the results against the calculations. This could be done by simply fixing the beam at one end by a clamping mechanism creating a cantilever beam structure. A uniformly distributed load as previously specified can then be applied using a hydraulic press. Depending on the value of deflection measured a dial gauge can be used to measure small values of deflection or a measuring calliper to measure the highest point of deflection from a set datum plane. The results of this experiment should be interpreted as the final values of slope and deflection of the beam and should be very close in comparison to the manual calculations. Again, close attention should be made to ensure the deflection value does not exceed 10mm during the testing.



Figure 5: This image shows an example of beam deflection testing for a simply supported steel I-beam. The load is being applied by a hydraulic press with instrumentation attached to measure the deflection.

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