

University of Wales Trinity Saint David
School of Engineering

Designing a Race Car Rear Wing:
Structural Design
Structural & Fluid Analysis
ACMA6010

Lewis Owen Nekrews
2008701
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Summary

The coursework explored techniques of optimization through methods of finite element analysis, using these to optimize an aerodynamic component with the goal of reducing its weight whilst remaining in a fixed state.

This study was built on what was assessed in the previous work on the aerodynamic behavior of a rear wing. The task was based on a simplified design of the carbon fiber feature of a race car for analysis in simulation and prototyping.

The first task in the brief involved researching methods of finite element analysis optimization, exploring their development over the years and how they benefit the industrial environment. The research study showed that the implementation of optimization methods has aided in finding a quicker and more effective solution for the optimum component. Its development in automotive and aerospace environments with methods of optimization to meet requirements aid design decisions that are not so heavily reliant on mathematical proofing.

Possible restrictions to using such methods like optimization software could be the lack of user knowledge and understanding in identifying a poor design solution. Like most simulation tools, users understanding of the feature applications besides from the set constraints are vital.

Future development could be through the accuracy of certain processes like meshing of a complex body. The more accurate the mesh, the more strain it puts on the user's devices giving the company a need for further investment in equipment to meet performance standards. The software also may not take into consideration all the loading angle without manual intervention, leaving inaccurate data.

Next tasks describe designing a carbon fiber wing using the orientation given in brief and the properties of the material. Accurate load cases were researched, applied to the model and baseline data was created to compare to the optimized variation of the simplified rear wing.

The optimization method was then implemented using the baseline structure given, where the variable is the number of plies in each orientation included. The results showed that greater thickness of material was required at the center of the composite, meaning that more stiffness was needed in that area to limit deflection. This was true for both load cases, horizontal and vertical, where zero degree layer orientation consisted of a greater number of plies than the transverse layers.

Prototyping was needed to compare both sets of data to confirm that the wing will be able to achieve target performance. Two methods of testing were preferred if the model was to be manufactured. One method explored the use of more practical equipment, using a generic hydraulic press to deflect the wing at the vertical axis. The second method of testing looked at was based on a professional standard to test the horizontal forces acting of the wing.

In conclusion the study demonstrated that by using sufficient software and understanding processes can generate an optimized component based on composite material. The analysis showed that a solution can be found using simulation technologies when certain properties are needed to be at a minimum, without compromising other characteristics.

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Introduction

The performance of a race vehicle when competing depends highly on its aerodynamic features such as the rear wing. Although the design process shows air flow analysis to be important, the structure's behavior is also addressed by teams, based on how the feature will behave under loading. This problem would be addressed by teams in racing organizations such as Ferrari (2023) who would allocate resources in development to create sufficient elastic deformation.

The rear wing is designed to flex to a certain degree when the vehicle moves at high velocity. This is to utilize the car's down effect and with accordance to Mitchel (2023), the feature, if designed correctly should flex downwards under loading to reduce drag forces. If the wing were to remain too rigid while the car is mobile, this would create more drag force to the structure and could even, in more extreme cases, plastically deform.

The wing experiences both compression and tension forces when the vehicle is in motion and would be considered a cyclic action as the applied force depends on the level of velocity it experiences. When subjected to bending, this would be regarded as a positive bending moment system by Hearn (1997) due to the shear stress distributed on the top of the wing. It would also be accurate to suggest that the top of the wing would be compressed whilst the bottom fibers are in tension.

The structure of interest is supported at both sides by two end plates while attached, assumed to be fixed, and to have six-degree freedom. Uploading the given design into SolidWorks (2023), the assumed deflection behavior was illustrated in Figure 1. The dual element without features, such as the gurney flap, is for simplification purposes, the assumption being that too many features in design may cause complications in simulation.

The main goal of the study was to design a fixed feature from composite materials with minimal weight to demonstrate a structural analysis while optimizing the features. Furthermore to analyze the results using computation engineering analysis techniques and how to compare then to acquisition study for a sufficient solution.

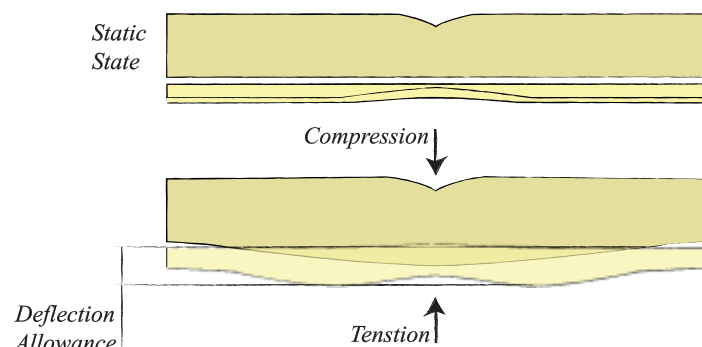


Figure 1 Comparison of Proportional Rear wing to Deformed Version
Positive Bending as described by Hearn (1997)

Finite Element Analysis & Optimization

Finite element analysis is a technique of solving differential equations and is considered by Rao (1999) to be replacing complicated mathematical problems with close estimations. He then follows to state that FEA may not give exact solutions compared to theoretical practices but considered it capable of finding a solution to solve a problem in engineering. It could also be stated that FEA has the main benefit of potentially solving multiple objectives rather than conventional methods which would only sensor singular. FEA is also an advantage as being able to solve for complex geometry with reference to Rathore (2019).

According to Mirendehdel (2017) FEA plays a central role in optimization techniques and can be described as a means of creating a more efficient product which is cost effective. The common type performed by engineers is topology optimization and is a technique that optimizes the design feature by minimizing unneeded volume from a domain. This then assists in dealing with certain constraints, like maximum amount weight of an object by increasing the amount material to a reactive region that is heavily strained and removing from area less impacted.

A second technique researched was shape optimization, which in accordance with Bouclier (2022) aims in finding the optimal shape from the topology optimized feature. This could be used in improving the structures to minimal mass or to maximize the rigidity. A variation of shape optimization in topography involves, according to Abby (2015) moving the elements away from their original datum. This offset would effectively increase such properties like stiffness. The advantage when comparing topography to shape optimization is the degree of freedom of nodal direction.

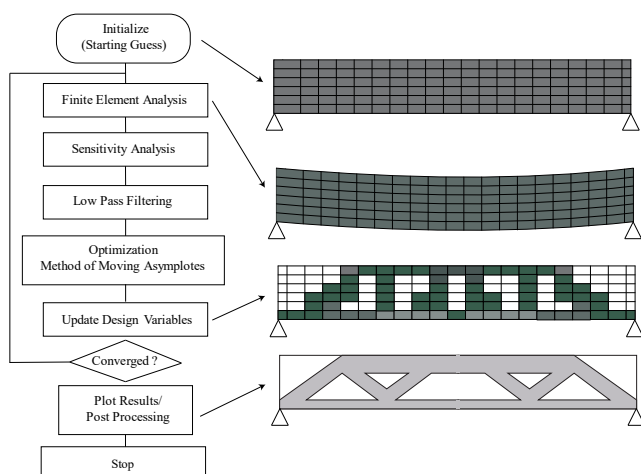


Figure 2 Flow chart Topology Optimization Diagram on a Isotropic Structure based on Sigmund (2004) Topology Optimization Study

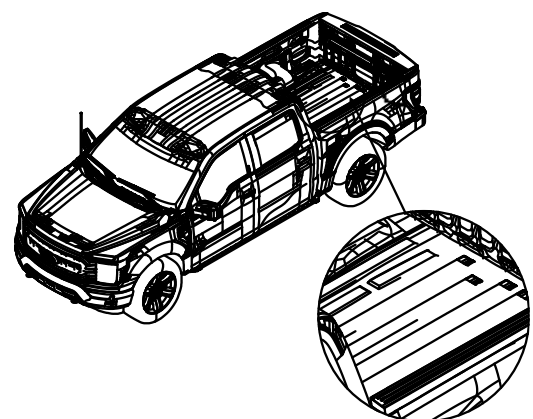


Figure 3 Topography Example on A Ford F-150 XLT Pick up Floor Panel Sketched from Model made by Darin L (2021)

History of Optimization & Future Predictions

Optimization is a method that was established through contributions from Newton and Lagrange to calculus, as explained by Rao (1999). In his study of engineering optimization, the foundation of calculus of variations was first implemented and the minimization of functions by Bernoulli & Lagrange was developed. The method of optimization of constrained problems, which has unknown multiples, was named after Lagrange.

Rao (1999) explained that the development of optimization was increased by means of computational methods which enabled the user to further explore new methods into optimization numerically. In the book Multidiscipline Design Optimization by Vanderplants (2007) it is suggested that high speed computers give the engineering team an ordered approach to design decisions, whereas previously it was heavily reliant on the skills of the user and their experience. Historically, optimization practices have matured where fields like automotive and aerospace have routinely implemented it in a design project. This more modern tool of optimization suggests engineering will avoid mathematical proofing and instead base it in their decision making, as Vandaplants (2007) mentions it being more pragmatic.

The way that optimization is used today is through computer algorithms, where the user must define an objective such as to maximize or minimize the stiffness or mass. With the inclusion of boundary conditions, the computer will then create algorithmic structure. Certain software packages aid the process to be carried out and can also take out the guess work for engineers. Most software packages are user friendly such as GENESIS according to Finiteelementanalysis.com.au (2023).

Though not used to its maximum in an industrial environment, due to certain application being restricted to how much material can be removed for example, FEA optimization reduces the amount of labor required from an engineer. It would still rely on user knowledge and understanding to recognize a poor design solution.

Future development predictions in FEA optimization would be to consider the limitation it holds, also further improvements such as the meshing process. Meshing would determine how accurate overall the analysis is to any FEA methods used.

An interview by enterfea (2023) with Dr. Manual Ramsair from CFEengineering (2023) described that at the end of the user optimization analysis the results will need to be verified. When applying load cases through simulation, the software does not consider certain angle changes unless manually coded into the software. Further advances in automatically applying various forces, and at different angle variation, could be introduced in future software packages. This would save in checking the stability and also material and loading uncertainties.

Simulation Plan

Coursework tasks included creating a model through simulation of the rear wing using the given material properties of each ply which are zero-point one millimeter's thick carbon fiber. The finite element model supplied in the coursework brief original material was made from steel isotropic.

The task described the creation of an obituary lay up of carbon fiber reinforced plastic, using twenty five plies, which would be considered far more layers than researched from Competitive Car Composites by Mcbeath (2016) who considered only six layers in his study.

Furthermore, it was required to optimize the structure in design studio, the objective being to minimize the mass of the structure with it remaining in a fixed state. This was built on the previous single analysis of the carbon fiber wing and used the same properties. The optimization was based around the number of plies used in each orientation and the software determined where layers should be prioritized.

A similar study was performed by Stewart Mitchel as racecarengineering (2021), He investigates how formula one teams optimize their wing for best performance and meet the FIA (2020) regulations of limitations of displacement. Similar study was by Bisagni (2004) although considered two loading variations to be able to simulate lift and drag displacement.

The task was to be optimized based on Bisagni (2004) study using FIA (2020) testing regulations with its loading and displacement constraints applied. This is on the assumption that to be able to correspond with previous study in aerodynamic simulation, the loading must be considered in horizontal and vertical axis.

During the study, the orientation of the plies was considered. The study Stress Analysis of Fiber Reinforced Composites by Hyer (1997) discussed the difference in deformation behavior. He suggested that the fibers with most resistance to bending depends on the orientation of the laminate layers and considers this arrangement influential to its components behavior under loading.

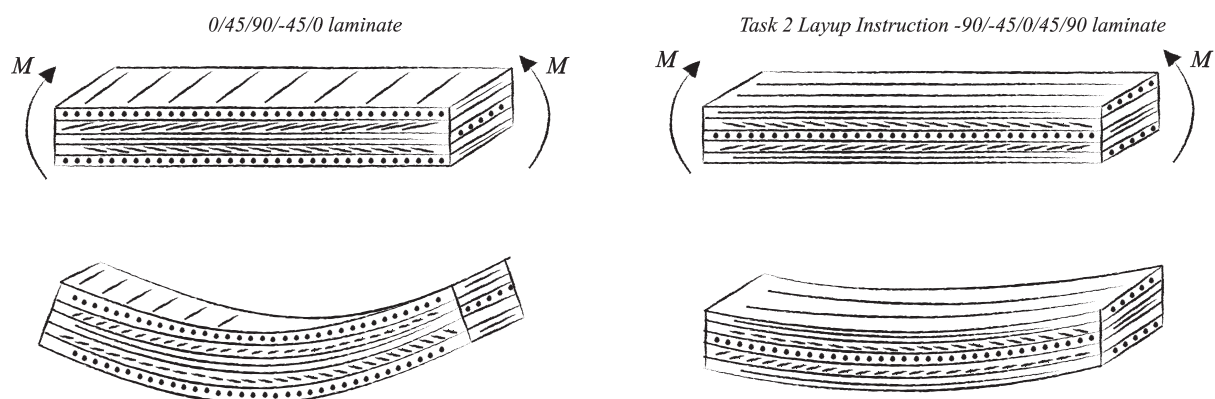


Figure 4 Layup described by Hyer (1997) Redrawn to Wing Design Five Layer Composite

Data Results

Testing Method Using Optimization Software															
Task	Run Type	Settings									Results				
		Material Description	Loud Case Direction	Loud Case Force (N)	Layup Orientation	Element Direction	Initial Thickness per layer (m)	Design Variables (m)	Decretre Design Variables (m)	Constraint minimum (m)	Variable Thickness (m)	Deflection	Objective Minium Mass (kg)	Stiffness (k) Force/Displacement	Stiffness/weight (N²/m) Stiffness/Mass*9.81
Task 2 & 3	Single Analysis	Orthotropic E_1 = 1.32E+11 E_2 = 1.32E+11 Nu_12 = 0.24 G_12 = 5.65E+9 G_1z = 5.65E+9 G_2z = 5.65E+9	Vertical =Z -1	200/5263=0.038N per grid Z=-1	-90/-45/0/45/90	0° runs length ways of vehicle	Layer 1 = 5E-4 Layer 2 = 5E-4 Layer 3 = 5E-4 Layer 4 = 5E-4 Layer 5 = 5E-4	None		0.002	0.0025	0.00068	1.88294	294117.6471	1532334.603
	Optimization Independent							Initial value = 5.0E-4 Lower bound = 1.0E-4 Upper bound = 1.0E-3	None		0.00135	0.0019	1.015958	105263.1579	1016411.681
	Optimization Concise								First discrete value = 1.E-4 Increment = 1.E-4 Number of additional values = 15		0.0017	0.0013	1.280434	153846.1538	1178686.89
	Single Analysis	Rho = 1540.0 Xt = 1.513E+9 Xc = 1.0E+9 Yt = 4.34E+7 Yc = 4.34E+7 S = 4.34E+7	Horiztonal = X -1	500/5263=0.0950029			None		0.005	0.0025	0.00046	1.88294	1086956.522	5662975.707	
	Optimization Independent						Initial value = 5.0E-4 Lower bound = 1.0E-4 Upper bound = 1.0E-3	None		0.000877	0.0048	0.6608591	104166.6667	1546282.71	
	Optimization Concise							First discrete value = 1.E-4 Increment = 1.E-4 Number of additional values = 15		0.013	0.0026	0.9791554	192307.6923	1926699.747	

Table 2 Testing Method using Simulation Software Based on Study by Bisagni (2004) & Also using Testing Regulations by FIA (2020)

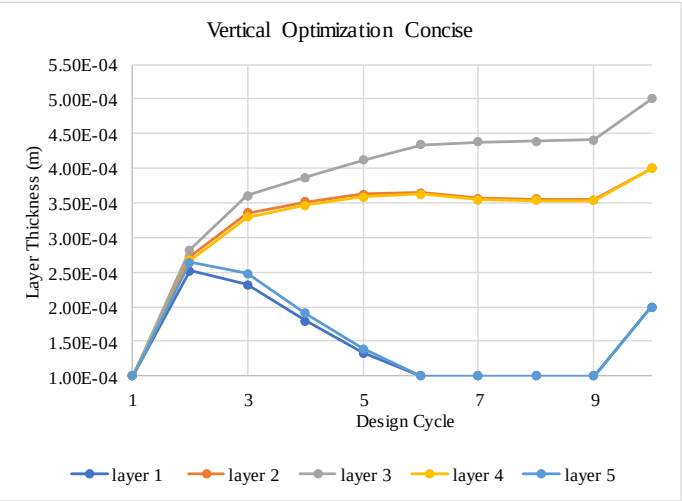
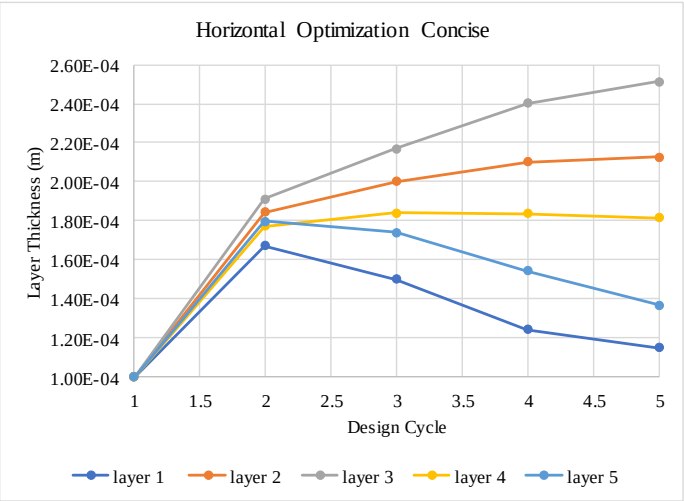


Figure 5 Graphs Displaying Design Cycle & Layer Thickness

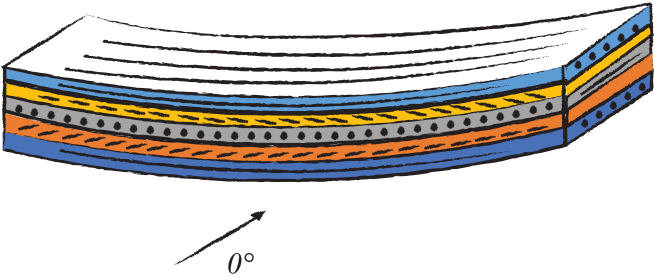


Figure 6 Layup Highlighted from Data

Results from Simulation

Looking at the results of single analysis because Carbon fiber is orthotropic, it showed that the stiffness value changes depending on the element direction. Moreover, the isotropic material has the same values of displacement in either direction due to its composition.

The brief described zero degrees facing the same as the direction of air flow, meaning that modulus (E_1), being of higher value, gives a greater resistance to deformation for the acting load.

Overall outcome is that the carbon fiber baseline structure did not deflect past the maximum displacement however, due to the weight of the material layers, it would be much too heavy to be considered acceptable for performance use. Malnati (2009) states that rear wing carbon fiber can be as light as four kilograms and this suggests that less material layers are being used in the process.

Optimization results from analysis were first implanted using independent variables which had the lowest amount of mass in the study. This method, however, does not take into account the manufacturability of the model and does not consider that plies are constrained by singular units and can't be split into small quantities.

For a more feasible study, the concise variable works with only whole plies and can be used further in development and not just a means of theory data with limited value. The concise data showed that compared to the original twenty-five plies structure, there was a reduction in weight by at least forty percent in each load case whilst not corrupting the displacement constraint.

For both studies of discrete and independent variables, the lowest amount of displacement was found to be the elements moving toward zero degrees orientation where layer thickness was high nearer to the center. This would support what Hyer (1997) stated that the importance of understanding how fiber angles influence response under loading and the stacking arrangement.

The position of the fiber proved to be the main obstacle affecting the loading capability. This was acknowledged in the book Design and manufacture of Composite structure by Eckold (1994) who states that fibers produced are highly anisotropic and produce high stiffness and strength in their direction of reinforcement, however when moved further away these properties fall rapidly. This was also investigated in an article by Anto (2019) who also confirmed that at the zero degrees orientation, the plies stiffness was at its greatest after experimenting using simulation software.

Prototype Testing

Manufacturing a prototype and testing would be necessary for teams to verify the result from simulation and to compare the data to the lab results. This was suggested by Jones (2018) in his study of the mechanics of composite structures needs validation. He stated that design variables associated with a composite structure cannot all be automated through computer technology.

Two methods were considered, the first suggested from Megson (2005) which was single point loading to the simply supported structure. It was determined that the most practical method to test the loading would be to use a hydraulic press, however modification would need to take place in order to fit such a large component with two elements. A specialized fixture could press both elements simultaneously, created from machined aluminum. This method was based on research from instron.com (2023) who specialize in material testing machines including hydraulic compression machinery, however the displacement would be physically recorded.

The Second method of testing explored was the pull back test which was sourced from Sommerfield (2021) who discussed the changes in testing rear wing for Autosport.com. This was proven to mimic the load case while the force moves the wing backwards as described by Noble (2020) at Motorsport.com. The testing involved pulling the wing back by tightening the cable, which was attached to the rear wing, creating the required force. The pull back testing equipment was operated while the prototype wing was attached to the vehicle, as per regulations by FIA (2020).

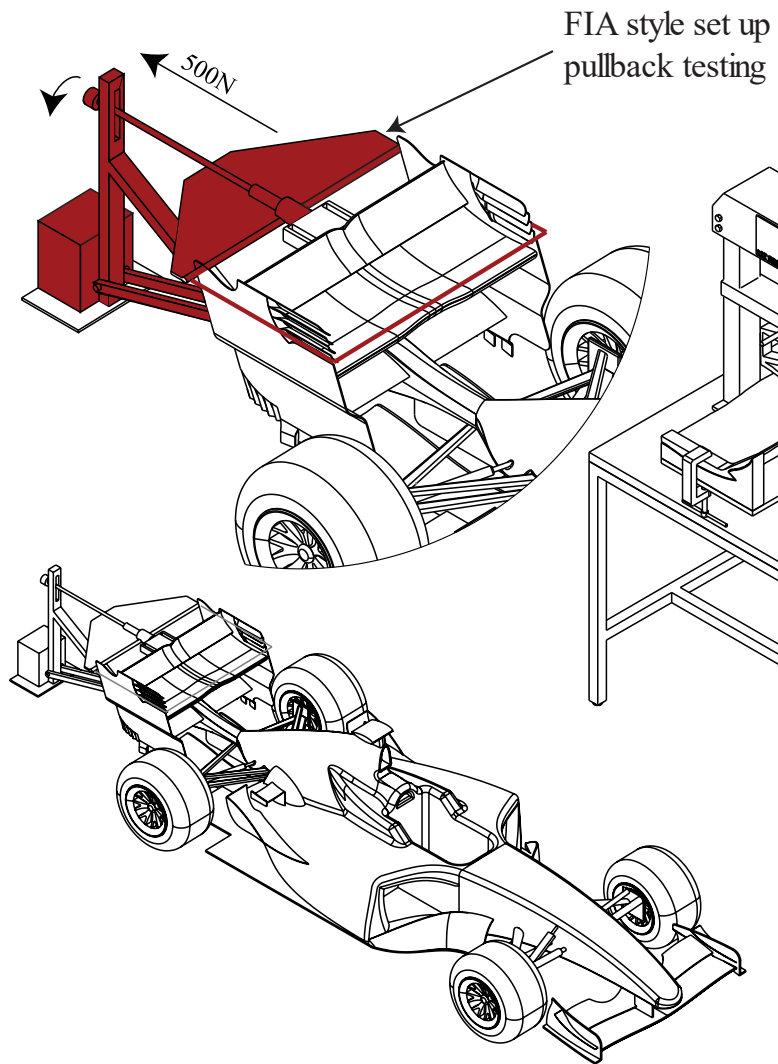
These tests lead to the first assumption when point bend testing, demonstrating that the material is linearly elastic and obeys Hooke's law. Therefore, it will relate to the calculations from simulation. Another assumption is that when testing vertical the load is evenly distributed once and correlates with simulation data.

Prototype Testing Procedure		
Task	Test 1 Vertical Lift Practical Method	Method 2 Drag Using FIA Testing Equipment
1	Weigh optimized prototype and log data to analysis	
2	Attach model to fixing jig of hydraulic press using clamps	Attach prototype to vehicle to create stable base for prototype
3	Manually lower the press handle until 200N of force is achieved	Rotate lever to increase pulling force to 500N
4	Record the displacement and Calculate the modulus to compare to simulation	

Table 2 Testing Procedure for both Testing Methods

Prototype Testing Schematics

Test B Hydraulic Hand Press



Test A: Hydraulic Hand Press

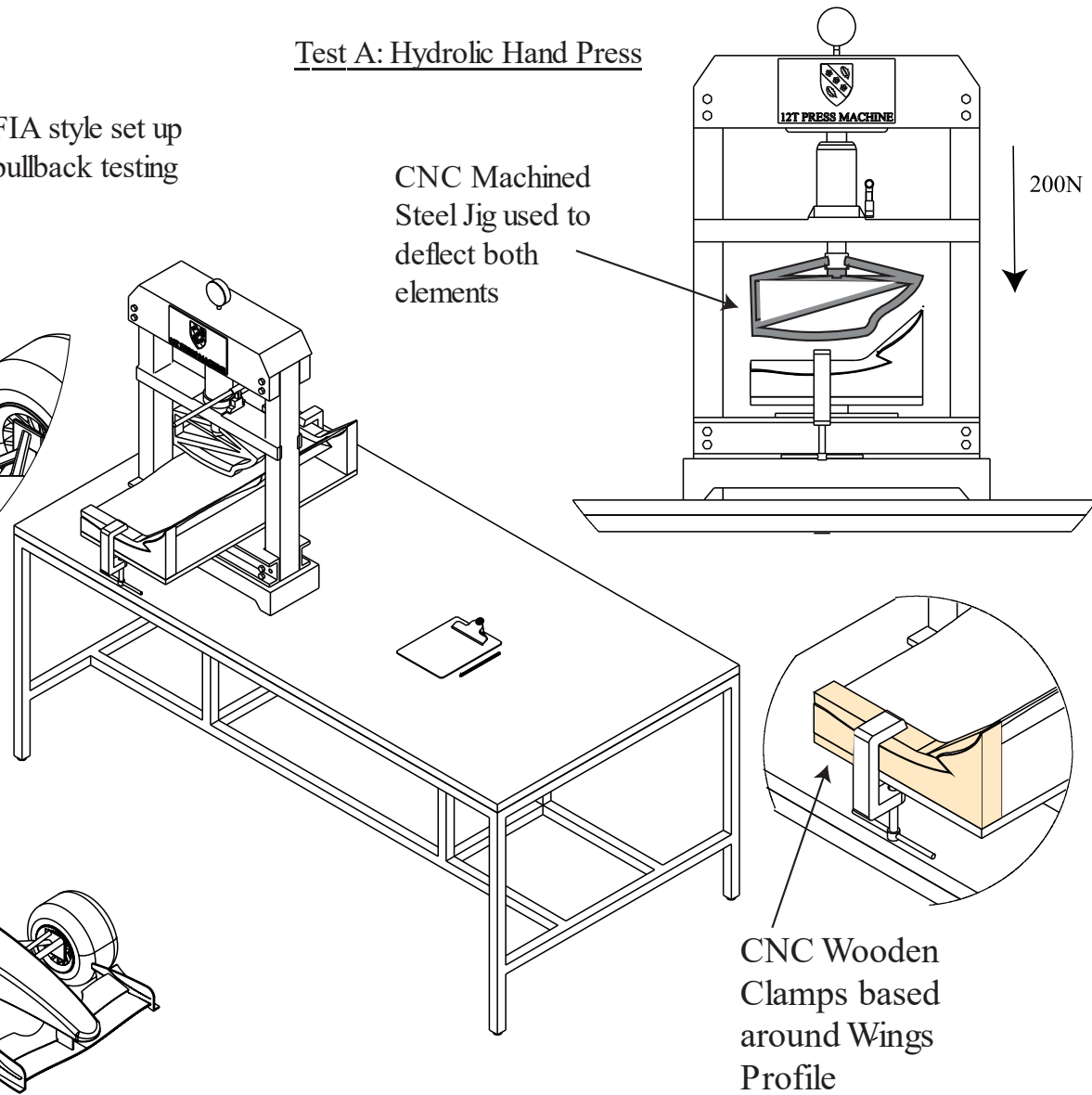


Figure 7 Testing Method A & B Schematics, F1 Race Car Designed by Majmader(2021) from GrabCad

Relating to Other Design Literature

In other areas involving structural design, such as aerospace, the implementation of carbon fiber is widely used on the wing design. These designs, however, are not normally associated with laminate carbon fiber but honeycomb sandwich panels. The two main advantages of using honeycomb over laminate, is that honey does not require ribs or inserts for support in accordance to Airpigz.com (2010) which means the model is lighter. Another main advantage is its resistance to shearing when a honeycomb center core is combined with laminated outer carbon fiber layers like an I beam as mentioned by Gibson (2015).

Optimization when designing an aircraft wing, could utilize similar methods as used with the rear wing of the race car but with the variable being core thickness, as studied by Nayak (2012) who's goal was to lower the amount of deflection while constrained to a certain weight.

Relating to other materials in motorsport, the epoxy resin prepreg material used in formula one would be considered a more complex optimization method as Gerald Perrin mentions in Motorposrt.com (2022) This would include the optimization of resins and fibers for the best performance achievable. Perrin (2023), who is associated with Solvay materials and supply advanced composite materials to greater stiffness to weight ratios. The properties of these competitive materials would assume greater than those implemented into simulations as even the commercially available product Solvalite 714 has under two grams per centimeter squared in density referring to the data sheet.

Also considered are limitations in material manufacturing and reinforcement of carbon fiber material. Permitters are acceptable stated by the FIA (2020), within article fifteen, for unidirectional carbon fiber with certain properties and core material such as aluminum, which were not included in the simplified model study. This would include the resin used compared in simulation where there was no specification for this.

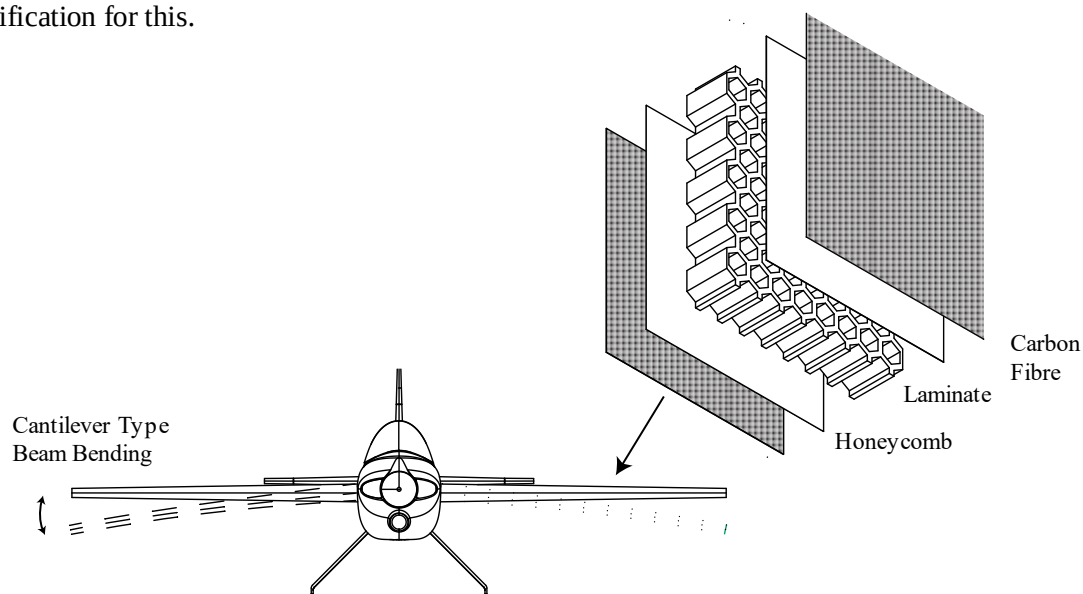


Figure 8 Laminated method mentioned by Gibson (2015) & Airplane Schematic

Conclusion

The issues focused in this report was the study of optimization techniques that are associated with finite element analysis. To discuss techniques of optimizing structures like rear wings to create the most efficient product possible such as topology optimization, used in motorsport to reduce the weight and increase the stiffness of components of a race car.

In addition, the study explores the design of a rear wing through FEA software and how to reduce weight while remaining in a so-called fixed state. The carbon fiber material and properties were given to create a baseline structure and could then be used to optimize the weight. It evidently reduced or increased the number of plies in each orientation and showed that most were needed closer to the center of the composition. This suggested, after research, the center plies benefited greater from being thicker than the outer layers because of higher stiffness at zero degrees angle orientation.

In addition, the development of a prototype was examined, which after research, would consider testing both vertical loading and horizontal due to direction in air flow the feature experiences. Both methods illustrated the testing process to study the deflection and would enable comparisons with the data in simulation. These methods of rear wing testing were researched to comply with motorsport regulations.

The value in the study was to identify that by using the correct method of optimization in simulation it could benefit the properties of components in such applications as racing wings. Furthermore, the outcome of the study showed that techniques in optimization simulation prove useful in development stages when creating a new component that requires maximum performance.

Further work

Further work could examine the behavior of the wing while loading is applied, through simulation using multiple load cases. As evidence shows in previous study in aerodynamic behavior, the forces acting on the wing are not of equal value, meaning that the structural study performed assumed uniformly distributed load and hence could not be correlated with previous study. Research found that SolidWorks (2023) has the option of uneven load case in its simulation function and experimentation in load case variation can be seen in Figure 9.

A method of bridging both studies, called multidiscipline design procedure, spoken about by Vanderplants (2007) considers it an adequate method to find the best shape airfoil. This involves calculating the aerodynamic loading on the structure first using software like SolidWorks (2023) then through optimization can determine a better design layup. Assessing the performance of multiple disciplines can help design teams meet objectives, without conflict, to create the best product.

Ideally to get correct results, using the same model from previous study will prove beneficial. Areas on optimization could be performed on aluminum inserts needed to support the end plates of the entire wing structure. Where the joints should be to support the structure could be optimized using the same method of simulation, this could use the variable of how many supports are required in the wing or the joining position of the supports. This was researched by Gomes (2020) who used topology optimization to reduce the mass within the airfoil. His study identified that most support was required at the front of the airfoil as a consequence of initial air impact.

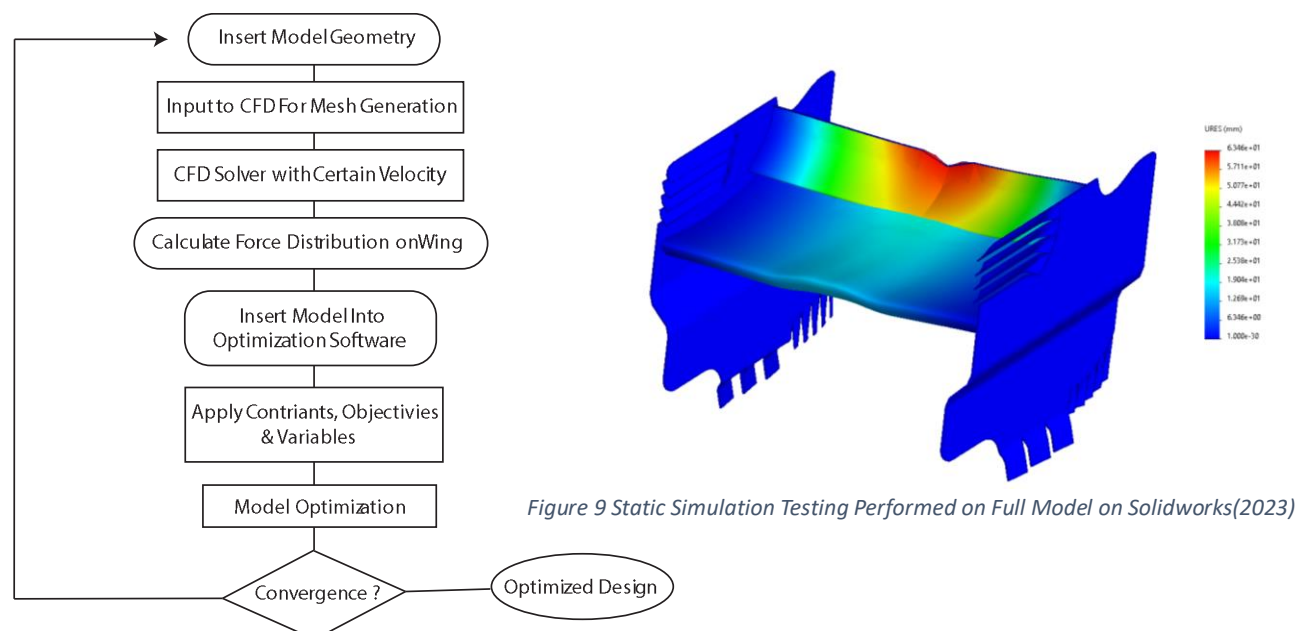


Figure 10 Multidiscipline Optimization as Studied by Vanderplants (2007)

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