WEIGHT REDUCTION IN A FORMULA ONE COMPOSITE WING

S Nevey  
CAE Manager

M Stephens  
Head of Structures

Jaguar Racing Limited
Bradbourne Drive
Milton Keynes
MK7 8BJ
s.nevey@jaguar-racing.com
m.stephens@jaguar-racing.com

Abstract: The development of Formula One cars is a continual process where designs never remain constant and even small improvements can be crucial. The application of optimization technology to the construction of composite lay-ups through simulation allows the consideration of many design iterations and provides a methodology for determining the optimum solution. This paper describes the development of a methodology for optimizing the fibre orientation and thickness of composite lay-ups. The optimization process has been verified through studies on a flat plate example subjected to a number of simple load cases. An optimization has then been performed on a generic formula one car front wing, applying the methodology developed for the flat plate. Simulations of the flat plate and generic front wing were performed using the linear static analysis code Altair OptiStruct. For the optimization of the generic front wing, the FIA loading constraint was met with a minimum additional mass. A discussion of the existing optimization process is given, along with further developments that will be made in this ongoing process.

Keywords: Uni-directional Composites, Optimization, Weight Reduction, OptiStruct, StudyWizard

1.0 INTRODUCTION

Jaguar Racing are not in the business of producing an end product but developing a prototype. That prototype development basically lasts for twelve months. It so happens that during that development period, the Grand Prix season starts. To design our “prototype” to such a state that it will run on a racetrack takes approximately four months. It can afford to be no longer, and does not need to be shorter. Therefore, the reduction of the lead-times is not an issue, the aim is to make the best use of the time available.

In basic terms, Jaguar Racing want to go through as many design iterations as possible, in the given time, in an effort to optimise every aspect of the car, to make it as competitive as possible. In this age of virtual product design and simulation, this can only be achieved with the use of CAE optimisation tools. Taking the drudgery of iterating design options away from the designer, and presenting him with an optimal solution. This is why Jaguar Racing is keen to employ tools, which will enable fast design iterations and optimization.
This paper provides an overview of the initial studies performed for an on-going programme of work. These assessments consider the static compliance of a flat plate and a generic front wing structure. Consequently, linear elastic orthotropic material response is used where the loads are applied statically. The objective is to determine the most efficient optimization technology and determine an analysis methodology to achieve the minimum weight of a structure.

2.0 COMPOSITE OPTIMIZATION OVERVIEW

2.1 Introduction

This section provides a brief overview of the issues encountered when performing size optimization studies of directional fibre composite laminates.

A number of optimization technologies are available to determine the optimum lay-up design (section 2.2). This study will identify the most efficient technology for Formula One components. Complementary to this activity, is the development of an analysis methodology to ensure that a reliable global optimum can be routinely achieved for the components (section 2.3).

Independent of the optimization techniques selected is the definition of the optimization problem. This requires the specification of a design objective, design constraints and design variables. Issues relating to the setting up of the optimization problem specifically for directional fibre composites is discussed (section 2.4).

2.2 Optimization Technology

Three leading optimization techniques (i.e. Design of Experiments, Gradient Based, Genetic Algorithms) are available to perform size optimization studies. This study will quantify the advantages and disadvantages of each of these techniques (Table 1).

<table>
<thead>
<tr>
<th>Optimization Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design of Experiments</td>
<td>Achieve a Global Optimum</td>
<td>Small No. of Design Vars</td>
</tr>
<tr>
<td>Gradient Based</td>
<td>Large No. of Design Variables</td>
<td>Achieve a Local Optimum</td>
</tr>
<tr>
<td>Genetic Algorithms</td>
<td>Discrete Variables</td>
<td>Small No. of Design Vars</td>
</tr>
</tbody>
</table>

*Table 1: Merits of Size Optimization Techniques*

New functionality in OptiStruct [1] allows size optimization using gradient based techniques. Currently, this functionality has not been implemented for a composite material. However, OptiStruct can perform a standard finite element analysis of an orthotropic composite laminate.
The StudyWizard [2] contains a variety of Design of Experiments techniques (e.g. Full/Partial Factorial, Taguchi, Plackett-Burman, Box-Behnken, D-Optimal, Central Composite Design (CCD) and User Defined), which can be used to generate a response surface. The objective and constraint can be computed by the baseline composite analysis facilities available in OptiStruct. In addition, a genetic algorithm [3] is available for ‘in-house’ use, which has been obtained specifically for comparison purposes.

Following a review of industry practice, there appears to be no consistent approach for the application of optimization techniques to composite laminates. Sophisticated applications have even combined all three of the techniques in an assessment procedure [4].

2.3 Optimization Methodology

The definition of a directional fibrous laminated composite requires the specification of a number of entities. The orientation of the fibre direction and the thickness of each ply within the laminate is required. The initial methodology considers a staged approach to optimization and considers fibre orientation and thickness optimization as two consecutive optimization studies (Figure 1).

![Optimization Methodology](image)

**Figure 1: Optimization Methodology for Composite Laminates**
2.4 Optimization Set-Up

**Design Objective**

The design objective for fibre optimization would be to minimise the compliance of the structure. This can be achieved by determining the global compliance of the component or a local compliance monitored at a single nodal location.

The design objective for thickness optimization would be to minimise the mass of the component. This is achieved by minimising the thickness of an individual ply or a ply bundle.

**Design Constraints**

A common constraint is nodal displacements since satisfying various regulations requires that deflection limits are not exceeded at specified locations. A stress constraint within the laminate may be specified. Compound stress measures have been derived (e.g. maximum stress theory, Hill and Tsai-Wu) to assess the failure of composite laminates. From these stress measures a failure index is determined which can be related to a margin of safety. This margin of safety can be quantified for every ply within the laminate and is used as the stress constraint.

The importance of the constraint type is dependent on the type of loading applied. The optimization process can select multiple constraint types without incurring a significant computational overhead. The stress related constraint can be included with negligible penalty, however, an Euler buckling constraint would not be included unless the design was driven by in-plane compressive loading.

**Design Variables**

For size optimization of composites, the selection of design variables is related to the manufacturing process and material. For fibre orientation, the designer has greater flexibility with uni-directional fibre than a woven cloth. For these studies the orientation is not limited and varies over the range 0° to 90°. The plies within a bundle will have the same orientation in order to ease manufacture.

In the optimization studies carried out, plies have been grouped together into bundles. The thickness of each bundle can be specified as a design variable. After the optimization is complete, the thickness of the bundles can be related to a number of plies.
3.0 FLAT PLATE OPTIMIZATION STUDIES

3.1 Introduction

This section details the initial studies performed on a composite flat plate. The objective is to subject a simple geometry to well defined loadings (e.g. uni-axial tension and compression, bending, shear and torsion). This simple numerical model will provide a testing ground to assess the performance of optimization techniques and the proposed analysis methodology.

3.2 Baseline Model Description

A square plate of dimensions 300mm x 300mm has been selected (Figure 2). The plate is idealised using 900 four node shell elements which are 10mm x 10mm. The plate is fixed along one edge while the opposite edge is subject to various unidirectional loads.

![Figure 2: Flat Plate Finite Element Model with Loads and Boundary Conditions](image)

The plate construction consists of a central core which is sandwiched between two bundles, top and bottom, which contain three plies in each bundle (Figure 3). The central core is 2mm thick and each ply is 0.5mm. The total plate thickness consists of twelve plies and the central core producing a baseline plate thickness of 8mm. The plies are considered as the same material which is a uni-directional carbon fibre. The response of this material is characterised using an orthotropic elastic material model.
3.2.2 Optimization Response

Fibre Orientation Studies

Four separate fibre orientation studies have been performed to verify the optimization process. The four load cases were tension, bending, shear and combined tension and bending. The objective of these studies was to ensure the optimization would orient the uni-directional fibres in the directions expected.

For the four load cases, the optimized angle of each fibre bundle is presented (Table 2). The contributing percentage of each bundle demonstrates the importance of each layer. This highlights the sensitivity of the displacement of the plate to fibre angle changes of each bundle.

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Optimized fibre angle ( (\theta^\circ) )</th>
<th>Contributing Percentage on Displacements (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bundle1</td>
<td>Bundle2</td>
</tr>
<tr>
<td>Tension</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bending</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shear</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Combined</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Results of Flat Plate Fibre Angle Optimization Studies

For all four load cases the fibre bundles have successfully oriented to the angles expected. When loaded in tension and bending the principal direction of the stresses is along the length of the plate, and therefore the fibres should orient in this direction.

For the shear load case, the principal direction of the stresses is at \( 45^\circ \) to the edge of the plate. This is shown clearly in Figure 4, where the flat plate maximum principal stresses have been plotted. The optimization has successfully orientated the fibres in this direction.
For the tension and shear load cases the contributing percentage of each fibre bundle is 25%. This is as expected because the loading is in plane and therefore the through thickness stresses are constant. For the bending load case the outer fibre bundles (bundles 1 and 4) have a more significant effect than the inner bundles. This is as expected because they are furthest from the neutral axis of the plate and therefore the stresses are higher.

The combined load case demonstrates how the optimization correctly identifies which is the most significant fibre bundle. When the tension and bending load cases are combined, superposition of the stresses leads to peak stresses in bundle 1 and almost zero stresses in bundle 4 (Table 2).

**Thickness Studies**

Two studies were performed for the thickness optimization. These were the tension and combined load cases. For both of these studies the fibre orientations were defined at the optimum angle of 0° for each bundle, obtained from the fibre orientation studies (Table 2).

For the tension load case an arbitrary displacement constraint was defined as a maximum 3.0e-3mm and for the combined load case the displacement was constrained to a maximum of 10.0mm. The two optimization studies demonstrate how the thickness of the fibre bundles has been reduced (Table 3). For the tension load case the bundle thickness have been reduced uniformly, whereas the lower bundles (bundles 3 and 4) have been reduced more than the upper bundles for the combined load case. This is because of the higher stresses in the upper bundles.
Table 3: Results of Flat Plate Thickness Optimization Studies

<table>
<thead>
<tr>
<th>Loading Condition</th>
<th>Optimized Bundle Thickness (mm)</th>
<th>Mass (kg)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bundle1</td>
<td>Bundle2</td>
<td>Bundle3</td>
</tr>
<tr>
<td>Tension</td>
<td>1.32</td>
<td>1.32</td>
<td>1.32</td>
</tr>
<tr>
<td>Combined</td>
<td>1.07</td>
<td>1.07</td>
<td>0.95</td>
</tr>
</tbody>
</table>

4.0 GENERIC FRONT WING OPTIMIZATION

4.1 Introduction

This section details the optimization studies performed on a generic front wing structure. The design of the structure is driven by the requirement to satisfy a deflection limit at the tip of the wing when a point load is applied [5]. The aerodynamic loads do not greatly influence the design and there are no legislative requirements to satisfy. This load is not considered in the optimization procedure. The assessment of the generic front wing follows the optimization techniques and analysis methodology applied to the flat plate structure (section 3.0).

4.2 Baseline Model

Figure 5: Schematic Representation of Generic Front Wing Lay-Up
A generic front wing was created to demonstrate the optimization method when applied to a realistic component. The profile of the main wing section was broken into five separate areas, three of which were considered as designable and two as non-designable in order to limit the size of the study. Figure 5 shows the composition of these sections and shows the symmetrical lay-up used. This lay-up of the composite material was created such that twelve design variables were defined. These were six fibre orientation angles and six corresponding fibre bundle thickness.

The front wing was fully constrained at the attached point to the nose cone and the FIA loading of 50kg was applied. For the optimization the vertical displacement of the loaded point was recorded, which was the end of the rear edge of the main wing section. The vertical displacement of the main wing section is shown in Figure 6. The displacement of the loading point was 7.22mm.

For the optimization of the fibre angles the objective was to minimise the vertical displacement of the loading point. The orientation of each bundle was varied between 0 and 90 degrees. The final orientation of the fibres is shown in Table 4 and shows that the optimum solution is obtained with all the bundles orientated at 0 degrees (along the width of the wing section). This appears to be a reasonable solution as the load condition is almost a pure cantilever type loading. A small amount of torsion will be introduced by the offset of the loading to the rear edge of the wing section, but the non-designable carbon fibre cloth should support this.
Table 4: Results of Front Wing Fibre Angle Optimization

As a result of the fibre angle optimization, the displacement of the loading point was reduced from 7.22mm to 6.75mm (Figure 7). The next stage of the optimization process is to optimize the fibre bundle thicknesses to meet the FIA loading requirement.

<table>
<thead>
<tr>
<th>Optimized Fibre Angle $\theta^\circ$</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundle1</td>
<td>Bundle2</td>
</tr>
<tr>
<td>Baseline</td>
<td>0</td>
</tr>
<tr>
<td>Optimized</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 7: Displacement Contour Following Fibre Optimization

Thickness Studies

For the optimization of the fibre bundle thicknesses the displacement of the loading point was constrained to a maximum of 5mm for the 50kg load case, as is defined in the FIA regulations. The objective of the study was then to minimise the mass of the wing, whilst not exceeding this limit. After the fibre angle optimization the displacement of the loading point exceeded the limit of 5mm, and therefore some additional mass would need to be added to the wing in order to increase its stiffness. The objective of the optimization was therefore to minimise this additional mass.

Figure 8 shows the vertical deformation for the main wing section of the final, optimized design, and demonstrates that the maximum deformation does not exceed the limit of 5mm. The final fibre bundle thicknesses are shown in Table 5, along with the mass of the baseline and final designs.
Figure 8: Displacement Contour Following Thickness Optimization

<table>
<thead>
<tr>
<th></th>
<th>Optimized Fibre Bundle Thickness (mm)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bundle1</td>
<td>Bundle2</td>
</tr>
<tr>
<td>Baseline</td>
<td>0.56</td>
<td>0.42</td>
</tr>
<tr>
<td>Optimized</td>
<td>1.40</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Table 5: Results of Front Wing Fibre Bundle Thickness Optimization

5.0 CONCLUSIONS

From the results of both the flat plate and generic front wing, a number of conclusions can be made. The objective of the flat plate optimization studies was to establish a methodology for the optimization of composite lay-ups for both fibre orientation and thickness. Optimization of the fibre angles for fundamental load cases was successfully carried out to verify the optimization process. The process of initially optimizing for fibre orientation and then subsequently minimizing fibre thicknesses was established.

The process of sequentially optimizing for fibre orientation and thickness has been applied to a generic front wing and has successfully developed a lay-up which meets the FIA loading requirement, whilst minimising the additional mass required.

This paper forms the basis of a continual development programme to establish improved methods of optimizing composite lay-ups of complex structures. In the further development of this technology a number of improvements are still planned. An initial step is to gain confidence in optimizing structures using more design variables, which will allow more flexibility of design solutions, leading to improved optimum designs. With the inclusion of more design variables it will be possible to optimize for
both fibre orientation and thickness concurrently, allowing interaction between these factors to be considered. A final stage will then be to consider discrete optimum solutions, particularly for fibre thicknesses, where only a finite number will be feasible.

6.0 REFERENCES


