OPTIMIZE THE OPTIMIZED: WEIGHT REDUCTION OF AN F1 COMPOSITE WING

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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 paper discusses the latest developments of composite optimization technology as part of the technical partnership between Altair Engineering and Jaguar Racing. The optimization methodology is based on a genetic algorithm and the finite element analysis software OptiStruct by Altair Engineering for the design of composite components in a Formula One car. The methodology is first tested on a generic front wing, and then applied for weight optimization of the front wing in the Jaguar R3 Formula One car for the 2002 racing season.

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

1.0 INTRODUCTION

In the development of a new Formula One car, the design process takes approximately 4 months and has to go through as many iterations as possible. In such a competitive environment small improvements can be crucial, and the use of a robust technology to produce the best possible design is an essential advantage.

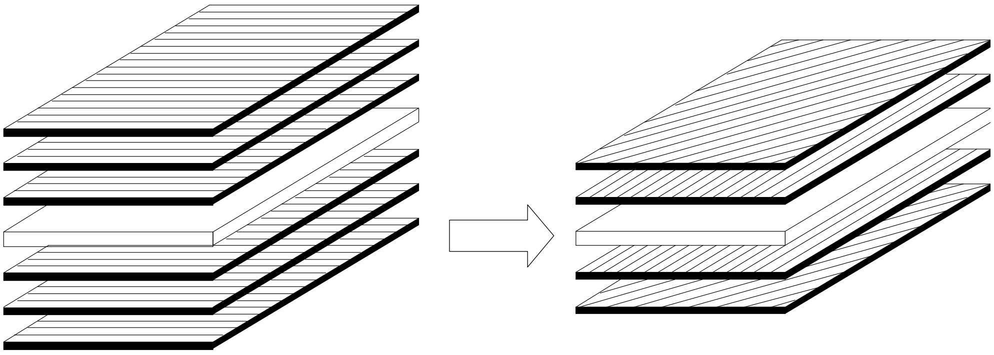
Following a review of industry practice **[3]**, there appears to be no consistent commercial approach for the application of optimization techniques to composite laminates.

Both Jaguar Racing and Altair Engineering have the common goal of developing technology, which will facilitate the rapid optimization of composite structures. For over two years a technical partnership has been established between Jaguar and Altair to develop composite optimization technology. Recent studies, discussed in this paper, have been performed through collaboration with the University of Bradford.

A genetic algorithm (GA) has been developed in order to search the optimum combination of discrete design variables (fibre orientation and number of plies) that produce the maximum structural stiffness at the lowest mass. Simulations of the composite components have been performed using the linear static analysis code Altair Optistruct **[1]**. An application is presented where the developed methodology is applied to the weight optimization of the Jaguar R3 front wing.

2.0 OPTIMIZATION PROBLEM

The definition of a directional fibrous laminated composite requires the specification of the fibre direction and the number of plies **(Figure 1)**. The ultimate objective of the optimization methodology is to automatically determine the optimum laminate configuration (eg. optimum number of plies and orientation of every ply).



Baseline configuration **Optimized lay-up**

Figure 1: Optimization of a Composite Laminate

The optimization problem is to minimize the weight $F_0(\boldsymbol{x})$ of a laminated composite component, subject to various constraints $F_j(\boldsymbol{x})$, usually nodal displacements. The design variables x are the orientation of the fibre and the number of plies, which have been grouped into bundles for manufacturing requirements.

$$F_0(\boldsymbol{x}) \rightarrow \min, \quad F_j(\boldsymbol{x}) \leq 1 \ (j=1,\ldots,M), \quad A_i \leq x_i \leq B_i \ (i=1,\ldots,N) \tag{1}$$

3.0 GENETIC ALGORITHM

A genetic algorithm **[2]** is a search technique based on computer implementations of some of the evolutionary mechanisms found in nature. As lifeforms in the biological world can adapt to a particular environment, the genetic algorithm attempts to solve a problem by genetically breeding an initial random population of candidate solutions over a number of generations.

The candidate solutions are typically coded into binary strings (chromosomes) and evaluated through a fitness function, which is a measure of how well they can solve the problem. Following Darwin's principle of survival of the fittest, individuals that perform better have a greater probability of passing their genetic information onto successive generations.

At each generation, changes are made to the competing designs in search for improvement. The better individuals are selected to reproduce with operators borrowed from nature, like crossover (sexual recombination) and mutation. The resulting offsprings are then decoded and tested against the rest of population. Like in evolution, not all changes are beneficial, so the weakest individuals will gradually be driven out of the population. This process is repeated until an optimum design can be reached **(Figure 2)**.

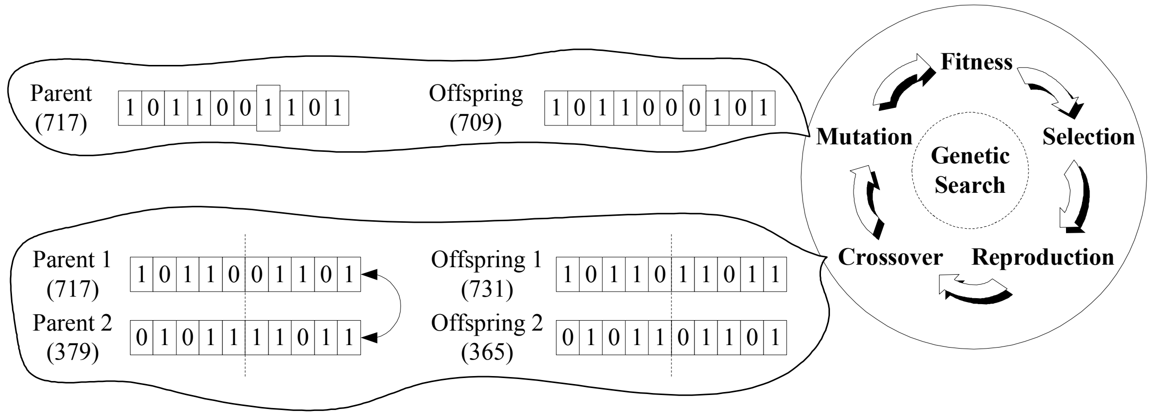


Figure 2. Genetic search

The strengths of genetic algorithms can be summarised by their abilities to work without prior knowledge about the problem to optimise, to work on a population of candidate solutions (reducing the risk of converging to a local minimum) and to optimise without secondary information such as gradients.

The large computation times are now less of a problem as increased computing power is relatively cheap and genetic algorithms can be efficiently implemented on parallel architectures. Also, since the evolutionary process is based on random changes, repeated genetic optimisations might often lead to different good designs. This aspect can be useful to present the designer with alternative solutions.

A genetic algorithm has been used in the design of the F1 composite wing because it is well-suited for discrete optimization problems, it can deal with a large number of design variables and it increases the chances to find a global or near-global optimum. When applied to complex engineering problems, a genetic algorithm has been proven to outperform traditional methods, and sometimes can find novel and surprising designs.

4.0 FLAT PLATE OPTIMIZATION STUDIES

4.1 Introduction

A genetic algorithm has been used to optimise the composite flat plate **(Figure 3)** proposed in the original paper **[3]**. For the optimization of the fibre orientation, the load cases of tension and shear have been considered, while for the thickness optimization the load cases were tension and combined (tension+bending).

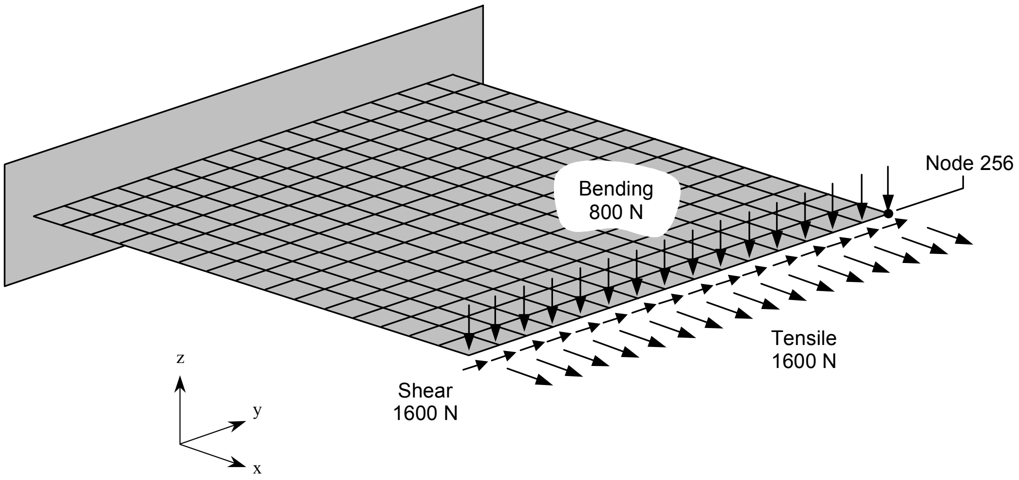


Figure 3. Flat plate model

4.2 Optimization results

Fibre orientation studies

The optimization problem is to minimize the displacement at node 256 **(Figure 3)**. The GA variable range is [-90°,90°] in increments of 5°.

For the two load cases in tension and in shear, the optimised angle of each fibre bundle is presented in **Table 1**. The GA solution for the tension load case produced an interesting result as the fibre of bundle 3 oriented to 5°**.** Looking at the boundary conditions, the edge was constrained in both the X and Y directions, not allowing a pure tension displacement. To confirm this observation, a new problem was defined with the edge constrained only in the X direction, in which case GA found the same solution as DOE.

For the shear load case, GA has the advantage that the variables can be defined in the range [-90°,90°], while DOE only allowed [0°,90°]. GA successfully oriented the fibres to reduce the displacement constraint by 35%.

Loading Condition	Optimization method	Optimized fibre angle ($\theta°$)				Displacement (node 256)
		Bundle1	Bundle2	Bundle3	Bundle4	
Tension	DOE	0	0	0	0	0.00679378
	GA	0	0	5	0	0.00679216
Shear	DOE	45	45	45	45	0.0305923
	GA	45	-45	40	40	0.0200124

Table 1. Results of Flat Plate Fibre Angle Optimization studies

Thickness studies

The tension and combined load cases were considered for thickness optimization. In both cases the fibre orientations were defined at an angle of 0° (optimum of fibre orientation studies).

The optimization problem is to minimize the mass subject to an artificial maximum displacement constraint of 3.0e-3 mm for the tension load case, and 10.0 mm for the combined load case. The GA variable range is [0,1.5] mm in increments of 0.05 mm.

As shown in **Table 2**, GA has outperformed the DOE studies in both load cases. Also, for each load condition, different GA solutions were proposed achieving the same final weight with different bundle thickness distributions. This demonstrates the capability of GA to find acceptable alternative designs.

Loading Condition	Optimization method	Optimized Bundle Thickness (mm)				Mass (kg)	Displacement (node 256)
		Bundle 1	Bundle 2	Bundle 3	Bundle 4		
Tension	DOE	1.32	1.32	1.32	1.32	0.77328	0.00257343
	GA	0.8	1.25	1.05	1.45	0.66816	0.00299142
	GA	0.7	1.35	1.1	1.4	0.66816	0.00299142
Combined	DOE	1.07	1.07	0.95	0.95	0.59472	9.17153
	GA	1.05	0.9	1.05	0.9	0.57456	9.83916
	GA	1.1	0.85	1.1	0.85	0.57456	9.83916
	GA	1.05	0.9	1.1	0.85	0.57456	9.83916

Table 2. Results of Flat Plate Thickness Optimization Studies

5.0 GENERIC FRONT WING OPTIMIZATION

A generic front wing **(Figure 4)** as described in the original study **[3]** was used to assess the performance of the GA with a realistic component The design variables were defined as the six fibre orientation angles in the range [0°, 90°] and the corresponding six fibre bundle thicknesses in the range [0, 2.1] (mm), As in the original study **[3]**, the thicknesses of individual bundles were considered as design variables.

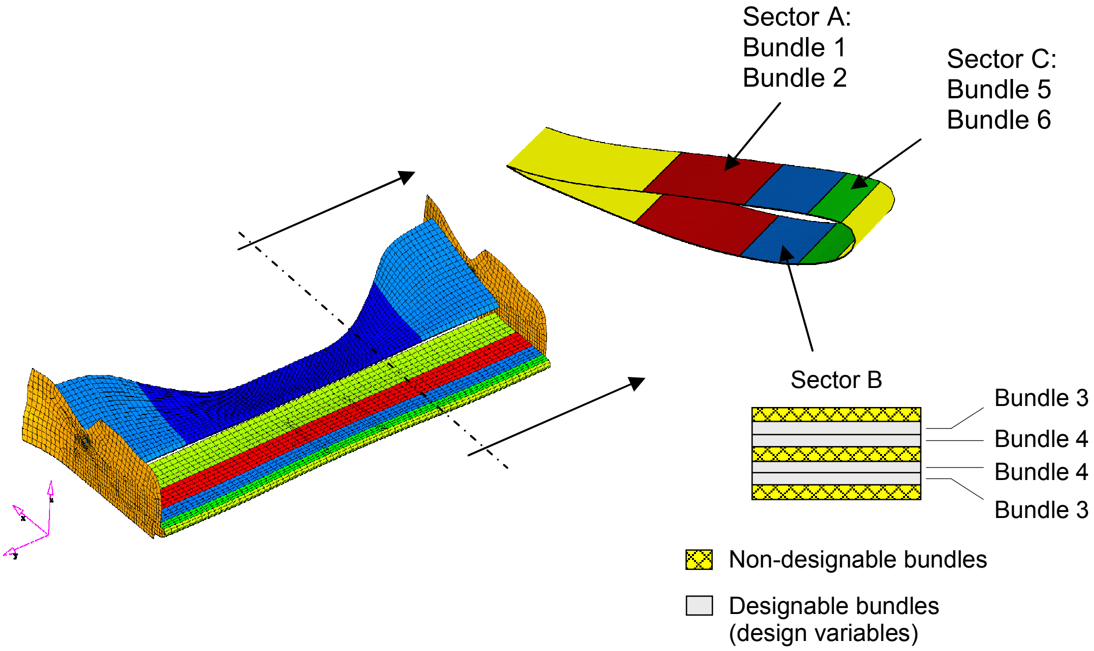


Figure 4: Schematic Representation of the Generic Front Wing Lay-up

Results

GA has improved the DOE optimization for the fibre angle optimization, as shown in **Table 3**. In the case of the bundle thickness optimization **(Table 4)**, the GA convergence was stopped at an early stage due to the time constraint to deliver the R3 front wing design. However, the solution is similar to DOE.

Optimization method	**Optimized fibre angle (θ°)**						**Displacement (mm)**
	Bundle1	Bundle2	Bundle3	Bundle4	Bundle5	Bundle6	
Baseline	0	90	0	90	0	90	7.22
DOE	0	0	0	0	0	0	6.75
GA	90	0	0	0	0	0	6.61

Table 3. Results of Generic Front Wing Fibre Angle Optimization

Optimization method	**Optimized fibre bundle thickness (mm)**						**Mass (kg)**
	Bundle1	Bundle2	Bundle3	Bundle4	Bundle5	Bundle6	
Baseline	0.56	0.42	0.56	0.42	0.56	0.42	3.9
DOE	1.40	1.40	0.32	0.00	1.40	1.40	4.5
GA	0.49	1.28	0.69	0.13	1.36	1.32	4.5

Table 4. Results of Generic Front Wing Fibre Bundle Thickness Optimization

6.0 R3 FRONT WING OPTIMIZATION

The final objective of this study was to optimise the weight of the front wing in the Jaguar R3 Formula One car for the 2002 racing season.

The baseline model was divided into 5 designable areas with 3 bundles in each section **(Figure 5)**. This lay-up defines 15 fibre angles and 15 number of plies. The allocation of design variables assumed that the model is symmetrical about the centreline of the wing.

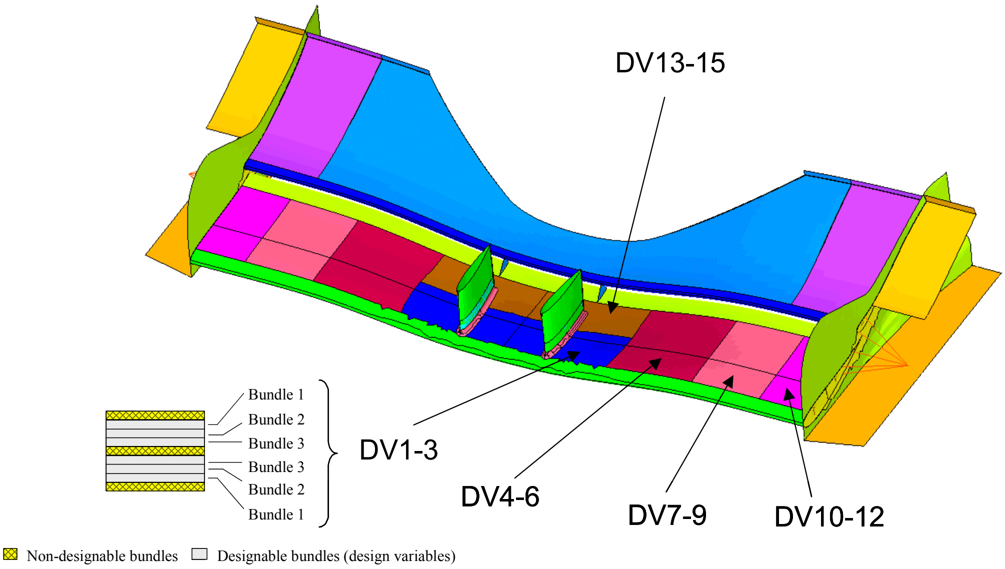


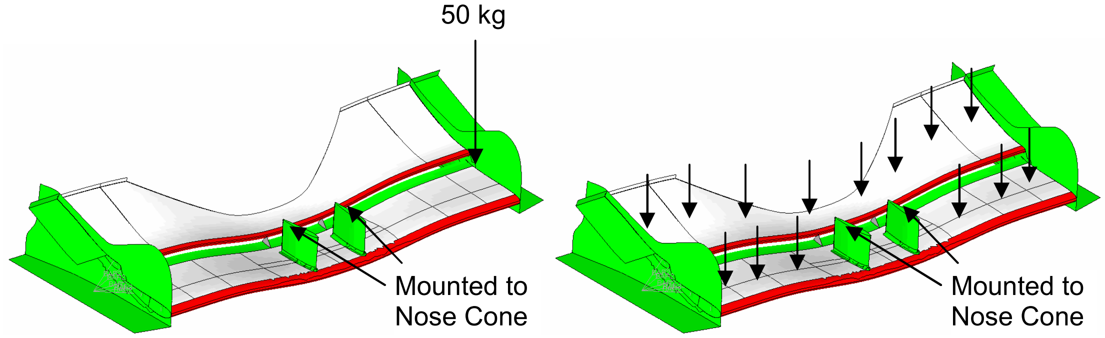
Figure 5: R3 Front Wing Lay-up

The problem was to minimize the mass of the wing, subject to the following normalised constraints:

- Maximum displacement under a 50 kg mass placed on the wing (FIA loading **[4]**) ≤ 1 mm **(Figure 6a)**.
- Maximum displacement under aerodynamic loading **(Figure 6b)** (calculated from a CFD analysis) ≤ 1 mm.
- Twist under aerodynamic loading (relative displacement of the leading and trailing edge) ≤ 1 mm.

The optimization was carried out for both fibre orientation and number of plies concurrently. The proposed methodology achieved a 5% saving over the baseline weight of the wing. The GA convergence history is plotted in **Figure 7**.

During the design process, both the shape of the wing and the aerodynamic loads were updated several times in order to introduce the latest improvements. Also, the competitive nature of Formula One requires solutions to be delivered within a few days so that they can be manufactured and tested. Accordingly, the GA was developed to be robust and to search for the best possible solution in every run and within the available time, generally stopping a full convergence toward the optimum.



(a) – FIA Loading **(b) – Aerodynamic Loading**

Figure 6. R3 Front Wing Loading

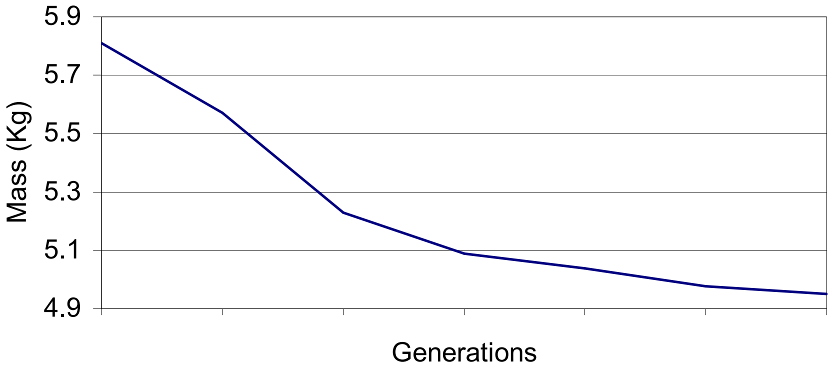


Figure 7. GA Convergence History

7.0 CONCLUSIONS

A methodology for optimizing composite lay-ups has been developed. It combines genetic algorithms with the finite element package Altair OptiStruct and solves concurrently the fibre orientation and the number of plies.

The results of the optimization have been used in two different ways:

- Initial results showed trends of the wing lay-up (e.g. biased more to bending in the middle of the wing and plies biased more to twist at the outer edge)
- Final results showed up a new direction for the wing lay-up and a variation was put onto the latest model of the front wing for the R3 Formula One car.

The studies performed in this paper highlight the continuing development of an optimization process for composite material lay-ups. Significant steps forward have been made to include large numbers of design variables, and to consider discrete design variable changes. The continuation of the development work will now aim to consider the application of the GA method to optimize a wider range of structures and to further refine the optimization process.

8.0 REFERENCES

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