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# Automation of Optimal Laminate Design

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*Abstract:* Composite laminates are in widespread use in the aerospace industry. As well as satisfying strength and stiffness criteria, the final laminate design has to be manufacturable in terms of compatibility between adjacent panels, thus introducing conflicting constraints on the allowed laminate stacking sequences. An attempt to automate the laminate design process is described. The method uses a mixture of a genetic algorithm and heuristics which are used to satisfy the various design and manufacturing constraints. Multiple zones are allowed, where each zone defines a panel together with a set of applied loads. Guide laminates and a blending methodology allow each zone to share common plies. This creates ply continuity across the structure and avoids the scenario seen in other laminate optimisation tools where each optimised zone contains unrelated laminates which are not practical from a manufacturing perspective.

*Keywords:* blending, composite, design, engineering automation, genetic algorithm, heuristics, manufacturing constraints, optimisation, laminate.

## 1 Introduction

The design of minimum weight structures using composite materials requires the laminates to satisfy structural requirements such as strength and stability. In addition, where a laminate is tailored to have differing numbers of plies and ply orientations for zones of a monolithic panel with different loading, the resulting design must have good manufacturability. This places a restriction on the valid laminate stacking sequences for adjacent zones.

This paper describes an automated method for the design of multiple zone laminates. Heuristics, such as limits on ply orientation percentages and balancing of laminates which are typically found in the aerospace industry are also included.

Optimisation of the laminates uses a genetic algorithm which provides a non-deterministic search of the solution space for the global optimum. It is based on the concept of natural selection and includes elements for population initialisation, parent selection, cross-over, mutation and selection of successive generations. Holland [1] is attributed with the original work on genetic algorithms which has been refined since. A guide based design approach [2] is used in conjunction with the genetic algorithm to cater for the presence of multiple related zones, and builds on the work of Salamonsen [3].

The genetic algorithm considers a population of guide laminates that satisfy the global constraints and requirements. The individual zones are blended by removing as many plies as possible from the guide laminate while still satisfying the local strength and stiffness requirements. This approach results in a design that is completely blended in terms of ply continuity across zones but with an associated weight penalty when compared to a solution where each zone is optimised independently. The guide based design may not be truly optimal, but tests show that the additional weight for a blended design compared to an unblended optimal design is small.

## 2 Method

The process has two main parts (Figure 1), guide generation or global optimisation and local or zone optimisation. The global optimisation begins by generating an initial set of laminates which are random with regard to number of plies and ply orientation. Heuristics are considered by applying constraints to the set of laminates and their stacking sequences are adjusted to satisfy the following.

1. Minimum and maximum total number of plies in the laminate.
2. Whether there are fixed plies at the middle, top and bottom surfaces or core in the laminate. Core can be specified as a fixed middle ply.

3. Minimum and maximum percentage of a particular ply orientation in the laminate.
4. The maximum number of plies of the same orientation that can be adjacent.
5. Whether the laminate is symmetric or not about the mid plane.
6. Whether the laminate is balanced or not. A laminate is balanced if, for every unidirectional ply at an angle $+\theta$ there is an identical ply at $-\theta$.

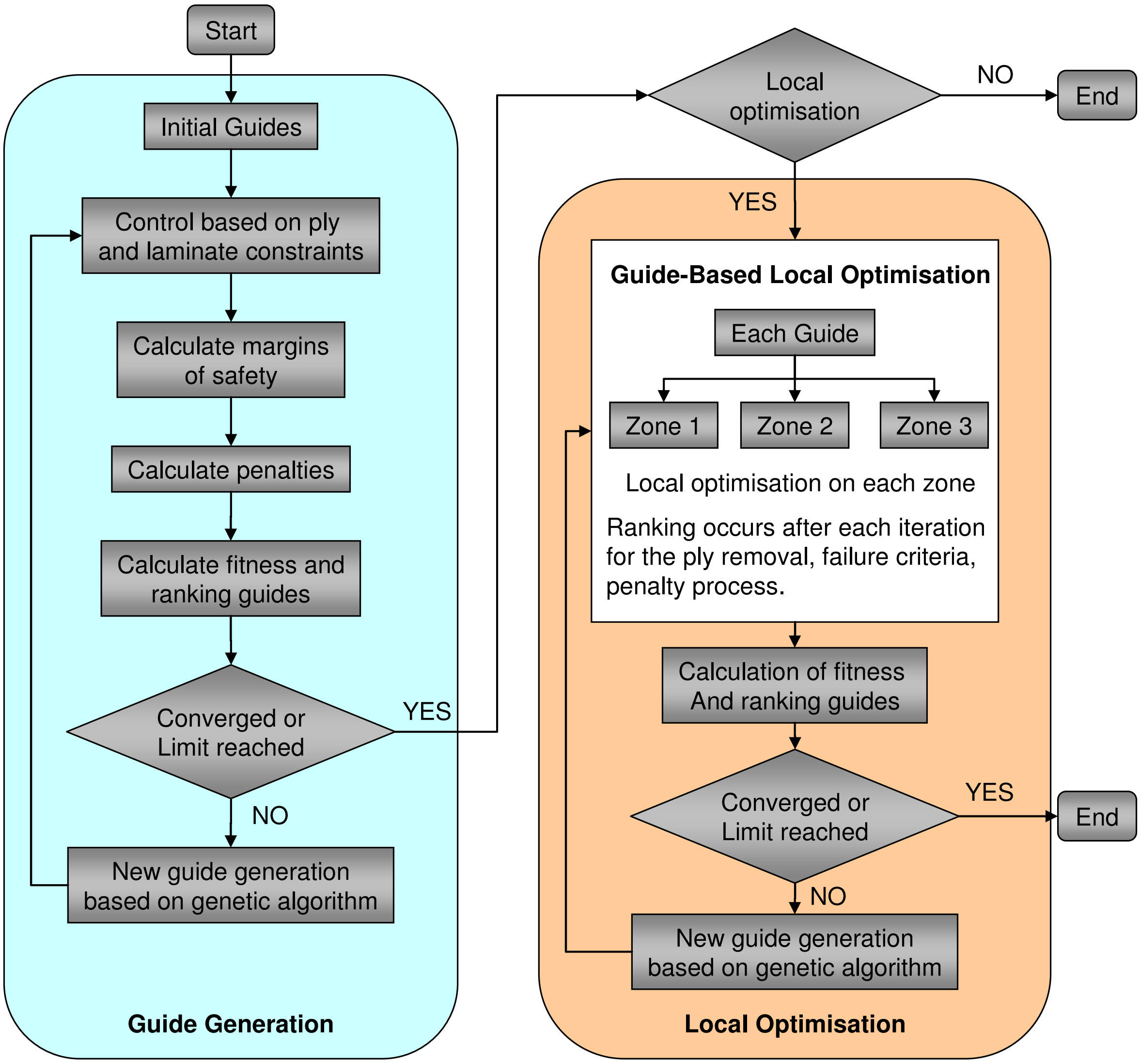


Figure 1. Process Flow

These heuristics vary to some extent between different aerospace companies and vary more widely in other industries where composites are used, but the algorithm is such that they can easily be changed or added to. The inclusion of heuristics in the algorithm negates the need for a subsequent step of adjusting the laminate to increase manufacturability. This additional step is often responsible for not achieving the most optimum design.

The resulting guide laminates are then analysed for static strength and buckling. Static strength is calculated using classical laminate theory [4, 5] and buckling analysis is performed with an internal GKN library of closed form solutions. These can easily be replaced with customer specific methods. The analysis results are then used to calculate a fitness value, F, for each laminate. The fitness value is used to determine which laminates will be used in future generations. The lower the value of F is, the more likely it is that the laminate will survive to succeeding generations of the genetic algorithm.

$$F = 1 + FI + BR + N + P \quad (1)$$

where FI is the ratio of applied to allowable strain, BR is the ratio of applied load to the critical buckling load, N is the total number of plies in the laminate and P is an overall penalty value which is a summation of individual penalty values multiplied by the quantity of plies which violate the design constraints of balance, contiguity and maximum and minimum percentages of particular ply orientations. P can be thought of as additional plies in the laminate which necessarily reduce the fitness of the laminate. Laminates with values of FI and BR which are greater than 1, thus indicating failure, have a very high value of F assigned to them.

The fittest 25% of the laminate population is then used as the basis for the next generation by applying random mutations by ply swapping within a laminate and between laminates (cross breeding). In addition the top 25% remains unchanged and an additional 25% of the population is generated in the same random way as the initial guide laminates.

The process then continues iterating until convergence which is defined as a set number of generations without improvement in the fittest design. The resulting set of guide laminates then satisfy the design, strength and stiffness constraints across all zones uniformly. These are then used as the starting set of guide laminates for the local optimisation block. This block is the same as the global optimisation block with the addition of a blending step which removes plies from the guide laminate for each zone until the removal of more plies would result in not meeting the strength and stiffness requirements. This removal can be done from the outer plies inwards, or in the case of a symmetric laminate from the middle plies outwards. One of the zones will remain with no plies removed. This is the critical zone for that guide laminate. The other zones will have fewer plies but will always have common plies with the guide laminate thus ensuring ply continuity across all zones. No concept of zone connectivity is present. Each zone effectively has ply continuity with every other zone. The fitness value, F, for each guide laminate is calculated as

$$F = \sum_{Z=1}^{n} F_Z \times A_Z \quad (2)$$

where $F_Z$ is the fitness value for each zone calculated using equation 1 and $A_Z$ is the area of the zone. The iteration then continues in the same way as the global optimisation block by generating a new set of guide laminates. Convergence is defined in the same way as the global optimisation block.

## 3 Example

Consider a structural panel consisting of nine zones with differing dimensions (Table 1). Material properties and allowables are shown for the carbon fibre fabric in Table 2. Load cases for each zone and those that apply to all zones together with the analysis type required are shown in Table 3.

Table 1. Zone Data.

| Zone | Size X (in) | Size Y (in) | Radius (in) |
|---|---|---|---|
| 1 | 10.000 | 15.000 | 100.000 |
| 2 | 12.000 | 12.000 | 90.000 |
| 3 | 12.000 | 10.300 | |
| 4 | 9.500 | 11.000 | 68.750 |
| 5 | 10.200 | 20.100 | 88.000 |
| 6 | 9.780 | 19.100 | 91.345 |
| 7 | 8.100 | 15.542 | |
| 8 | 5.450 | 4.880 | |
| 9 | 18.130 | 12.448 | |

Table 2. Material Properties

| Property | Value |
|---|---|
| $E_{11}$ (psi) | 9.0E+6 |
| $E_{22}$ (psi) | 9.0E+6 |
| $G_{12}$ (psi) | 1.0E+6 |
| t (in) | 0.008 |
| $\nu_{12}$ | 0.05 |
| $\rho$ (lb/in$^3$) | 0.06 |
| $\varepsilon_{T1}$ | 0.005 |
| $\varepsilon_{C1}$ | 0.004 |
| $\varepsilon_{T2}$ | 0.005 |
| $\varepsilon_{C2}$ | 0.004 |
| $\gamma_{12}$ | 0.008 |
| $\tau_{13},\tau_{23}$ (psi) | 10.0E+3 |

Table 3. Loading Data.

| Zone | Load ID | Static | Buckling | Nx (lb/in) | Ny (lb/in) | Nxy (lb/in) | My (lbin/in) |
|---|---|---|---|---|---|---|---|
| All | A.1 | ✓ | ✓ | 290.45 | | 23.44 | |
| All | A.2 | ✓ | ✓ | 323.70 | | | |
| All | A.3 | ✓ | | | | -1165.40 | |
| All | A.4 | | ✓ | -38.70 | | 194.50 | |
| All | A.5 | ✓ | | 551.66 | 1176.20 | 1103.20 | |
| 1 | 1.1 | ✓ | | 201.30 | | | |
| 1 | 1.2 | ✓ | | -323.60 | 103.20 | 78.93 | |
| 1 | 1.3 | ✓ | | | 548.90 | | |
| 2 | 2.1 | ✓ | | | 5307.80 | | |
| 2 | 2.2 | ✓ | | 2398.70 | | | |
| 2 | 2.3 | ✓ | | 55.30 | 2208.70 | 1134.50 | |
| 3 | 3.1 | ✓ | | 3583.80 | 135.70 | 2237.00 | |
| 3 | 3.2 | ✓ | ✓ | -449.00 | | 278.00 | |
| 3 | 3.3 | ✓ | | | 4657.30 | 4192.80 | |
| 3 | 3.4 | ✓ | | 3669.00 | 2235.90 | 2354.10 | |
| 3 | 3.5 | ✓ | | 2559.40 | 3972.40 | 1567.90 | |
| 4 | 4.1 | ✓ | ✓ | 248.90 | | 145.87 | |
| 4 | 4.2 | ✓ | ✓ | 254.80 | | 256.70 | |
| 7 | 7.1 | ✓ | ✓ | -268.90 | | -134.55 | |
| 8 | 8.1 | ✓ | ✓ | -65.88 | | 130.78 | |
| 8 | 8.2 | ✓ | | 2268.00 | | 2215.10 | 112.76 |

The resulting design is constrained to be a symmetric laminate. There is a limit of 3 adjacent plies which can have the same orientation, and minimum and maximum values of 0% and 100% on the allowed quantities of 0°, ±45° and 90° orientations. There are no fixed plies. There are 50 guide laminates in each population. Runs were done with blending from the outer plies inwards and from the middle plies outwards.

Results for both blending options are shown in Table 4. One advantage of the algorithm is that even with one blending method it produces a number of equally optimum designs which generally have different layups but the same number of plies, allowing the designer a choice for the final design. In addition the two blending options can produce quite different layups but with the same number of plies for each zone.

For nine zones with the load cases and analysis types shown in Table 3 there are 84 analyses required for each iteration of the global optimisation loop. The same number is required for the guide laminates in the local optimisation loop. Additionally, analyses are required for each step of the zone blending when plies are being removed. The number of these cannot be estimated a priori. In the case of blending from the surface inwards in this example there were 71 generations in the global optimisation block and 43 generations in the local optimisation block. This gives a minimum of 9576 analyses of strength or buckling to be performed. It can be seen that the time consuming part of producing a composite panel design is taken in the structural analysis routines. This is a well known disadvantage of genetic algorithms in general. Obviously, the analysis routines that are used in the application should be as efficient as possible with a preference for simple closed form solutions over other methods for the buckling analysis. Due to the randomness inherent in the algorithm, different runs with the same data take different times. In this case run times were typically 4 to 6 minutes on an Intel® Xeon™ 3.4GHz desktop PC.

The randomness of the genetic algorithm also results in different solutions for different runs with the same data. It has been noted that at times a slightly heavier solution is the result with typically one or two extra plies in one zone. This is also a function of the input parameters such as the value of the number of generations without improvement which defines convergence. Results show different laminates for the two different blending directions but with equal numbers of plies and the same weight of 8.45 lb. By contrast, an unblended solution has 10, 18, 22, 8, 10, 10, 16, 20 and 12 plies respectively for the 9 zones with a weight of 8.07 lb. The global blending process has thus added extra plies to zones 2 and 3 with a weight penalty of 4.7%. This indicates that if the blended design is not truly optimal, it is close to being so for all practical purposes.

Table 4. Final Design Solution (half laminate).

| Global Ply | Zone | | | | | | | | | Zone | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 (surface) | | | 45 | | | | | | | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| 2 | | | 45 | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | | | 45 | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | | 0 | 0 | | | | | 0 | | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| 5 | | 0 | 0 | | | | | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 |
| 6 | | 45 | 45 | | | | 45 | 45 | | | 45 | 45 | | | | 45 | 45 | 45 |
| 7 | | 0 | 0 | | | | 0 | 0 | | | 0 | 0 | | | | 0 | 0 | |
| 8 | | 0 | 0 | | | | 0 | 0 | 0 | | 45 | 45 | | | | 45 | 45 | |
| 9 | 45 | 45 | 45 | | 45 | 45 | 45 | 45 | 45 | | 45 | 45 | | | | | 45 | |
| 10 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | | 0 | 0 | | | | | 0 | |
| 11 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | | | 45 | | | | | | |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | 45 | | | | | | |
| 13 (mid) | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | | | 0 | | | | | | |
| No. Plies | 10 | 20 | 26 | 8 | 10 | 10 | 16 | 20 | 12 | 10 | 20 | 26 | 8 | 10 | 10 | 16 | 20 | 12 |
| | Blend Inwards. Weight=8.45 lb | | | | | | | | | Blend Outwards. Weight=8.45 lb | | | | | | | | |

## 4 Comparison with a manual approach.

A traditional approach was applied to the above problem. The process involved using available laminate analysis tools but optimisation was done manually by mimicking to some extent the automated method. The most critical zone for strength and buckling was determined and then the laminate for that zone was manually adjusted and reanalysed a number of times until it was judged that the best solution had been found. The laminates for the other 8 zones were then determined by removing plies from the critical zone laminate.

Table 5. Manual Design Solution (half laminate).

| Global Ply | Zone | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1 (surface) | | | 0 | | | | | | |
| 2 | | | 0 | | | | | | |
| 3 | | | 45 | | | | | | |
| 4 | | | 0 | | | | | | |
| 5 | | | 0 | | | | | 0 | |
| 6 | | | 45 | | | | | 45 | |
| 7 | | 0 | 0 | | | | | 0 | |
| 8 | | 0 | 0 | | | | | 0 | |
| 9 | | 45 | 45 | | | | 45 | 45 | |
| 10 | | 0 | 0 | | | | 0 | 0 | |
| 11 | | 45 | 45 | | | | 45 | 45 | 45 |
| 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| 15 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 (mid) | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| No. Plies | 10 | 20 | 32 | 10 | 10 | 10 | 16 | 24 | 12 |
| Manually Blended. Weight=8.96 lb | | | | | | | | | |

The final design would be different depending on the engineer designing the laminates. A more experienced engineer might be able to produce a solution that took less time and was lighter due to the application of knowledge about how composites behave under different loading conditions and the effect of different stacking sequences on the structural response. In this case the design was completed by an experienced engineer without knowledge of the automated solution.

Results (Table 5) show that the final design weight is 0.51 lb greater than the automated design, equating to a weight penalty of 6.0% compared to the automated solution and 11.0% over an automated unblended solution. Including data preparation and input, the time taken to produce the design was 10 hours which compares with 1 hour for the automated method. Additionally the manual approach produced one design whereas the automated method produced many.

## 5 Conclusions and recommendations

Design of minimum weight composite material structures which satisfy structural and manufacturing requirements, whether in aerospace or other industry applications, can be successfully achieved using guide laminate based blending and a genetic optimisation algorithm. A test case shows that the method generates a low weight design which for practical purposes is optimal. The ability of the genetic algorithm to generate multiple designs of equal weight along with the ability to control the design through options such as blend direction and heuristics provides a strong justification for using the method. The blending methodology ensures that the resulting designs are easily manufactured due to ply continuity across multiple zones. The automation of what is a time consuming design process gives a practical final design in a fraction of the time required by traditional manual design optimisation methods.

Future work includes refining and increasing the efficiency of the supporting analysis methods, introducing the concept of zone connectivity and allowing the design of sandwich structures where the core is allowed to be placed at any position in the laminate.

## 6 Acknowledgements

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