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Composite Optimization Techniques for Aircraft Components Structural Sizing

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Abstract

Optimization techniques for sizing (typically parametric optimization using size and shape techniques) and topology optimization to get optimum conceptual designs has been widely used in Airbus for many years with metallic and composite structures. The challenge in the case of composite structures optimization is to manage the variation of the mechanical properties with the thickness and stacking sequences used in the laminate, the design constraints and manufacturing process. Different methods, investigated by Airbus, which can be easily implemented by stress engineers in the daily work to face the sizing of composite structures made of laminates are presented, discussed and compared.

1. Introduction

During the last decades optimization algorithms have been widely used by airframe departments within Airbus to reduce structures weight while meeting the strength and functional structure requirements (by the implementation of different type of constrains as stress, stiffness, frequency…). One of the first published applications showing the benefits and capabilities of the optimization applied to aeronautic structures can be found in Ref [1]. Since these first applications, the use of the optimization techniques, mainly embedded in finite element models, has grown jumping from specialized departments fully dedicated to optimization activities to the present in which optimization techniques has become an additional daily tool used by stress engineers to generate enhanced structures. However, the implementation of these optimization techniques in the daily work of the stress engineers has supposed a challenge for two main reasons.

As mentioned before, originally, structure optimization was performed within Airbus and other aeronautic companies by the creation of specific optimization centers fully dedicated to resolve overweight issues detected during the development phases of a new aircraft. In many cases, these optimization centers were made by a reduced number of stress or simulation engineers working in close collaboration with the optimization solver developers. For this reason, optimization knowledge remained for a period of time in an expert mode and restricted to few engineers within Airbus. Little by little, the dissemination of mentioned knowledge started to be spread along the stress departments to be applied not only to resolve critical situations associated to overweight during the development phases but also in the daily work of the stress engineers to calculate structures associated to modifications and repairs.

Moreover the implementation of the optimization within the design process altered the traditional way of working, especially the relations between design and stress departments. Optimization driven design process became a reality and airframe departments had to adapt their processes to this new design philosophy.

These barriers were overcome and an extensive use of the structure optimization techniques become a reality but dedicated mainly to metallic structures. Optimization of composite structures, mainly laminates, results more complex than metallic structures due to the variation of the mechanical properties with thickness and stacking sequences used in the laminate, the design constraints and the specific manufacturing process. These requirements, not always embedded in the FEM optimization solvers produced that composite structure optimization remained, as originally, in expert mode only applied by a reduced number of expert optimization engineers.

The main objective of the methodologies presented in this publication is to remove this barrier between the current use of structure optimization techniques between metallic and composite structures providing stress departments with means to apply composite structure optimization in the daily work.

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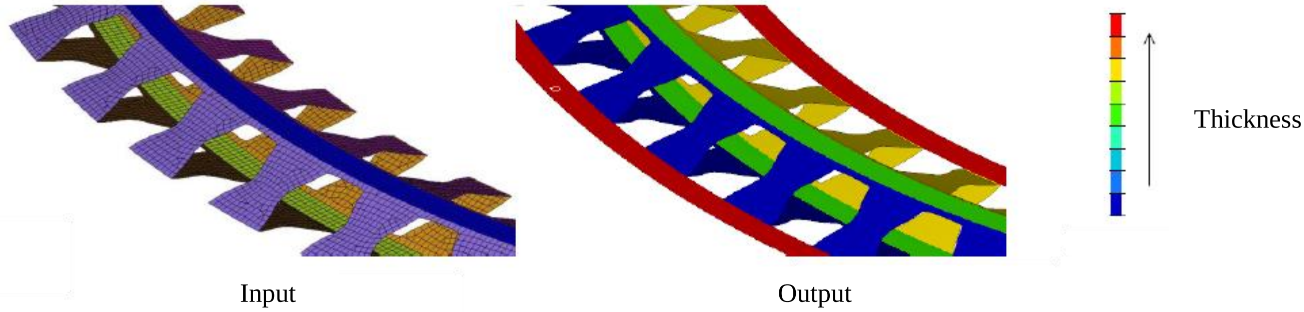
2. Structure Optimization Techniques

Composite optimization methodologies discussed in this publication are based on optimization techniques implemented in FEMs well known by the structure optimization community. Hereafter these techniques are briefly described.

- Size Optimization. In FEMs, the behaviour of structural elements such as shells, beams, rods, springs, concentrated masses… are defined by input parameters like shell thickness, cross-section properties, stiffness… Size optimization provides stress engineers with an automated method to modify mentioned parameters to search the optimal design.

  Figure 1 shows an application example of this technique used for the sizing of a space launcher structure (separation rings). Each colour in the input picture represents a different property (thickness value) which is turned into design variable for the optimization analysis.

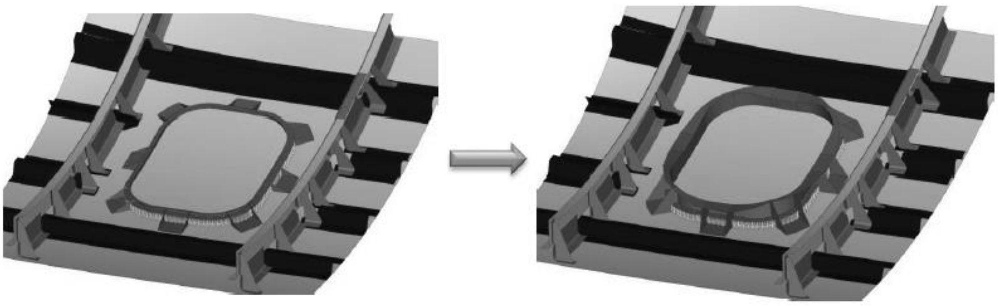


Input Output

Figure 1: Size Optimization Example

- Shape Optimization. This Technique represents an automated method to modify structure shape based on predefined shapes (design variables) to find the optimal dimensions of the analysed structure. Within the FEM environment, predefined shapes are defined by the grid point locations. Shape optimization technique modifies these locations along the optimization iterative process.

  Figure 2, shows an application example of this technique used for the sizing of a window frame which attempted to reinforce the window area to increase the first window natural frequency.



Initial Concept Optimized Design

Figure 2: Shape Optimization

Size and Shape optimization techniques can be used simultaneously allowing stress engineers to optimize any dimension of structures which can be idealized by 2D FEMs.

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- Topology Optimization. Probably the most known optimization technique. This method provides an optimized material distribution, within a predefined design space, concentrating the material where is actually effective fulfilling the constraints applied. Typical topology optimization algorithms, based on SIMP method [2], apply to each finite element a fictitious density value between 0.0 and 1.0. Voids in the new design are defined by elements whose density value tends to 0.0 whereas the load paths where the material must be located are defined by the elements whose density values tend to 1.0.

- Free Size. This technique represents a variation of the size technique but applying the thickness variation, design variables, to any single finite element of the 2D model. It can be considered an alternative technique to topology optimization for 2D models, allowing more design freedom since a continuous variation of thickness is provided in contrast to 2D topology optimization. Figure 3 illustrates the different output obtained for the same 2D optimization analysis using both, topology and free size.

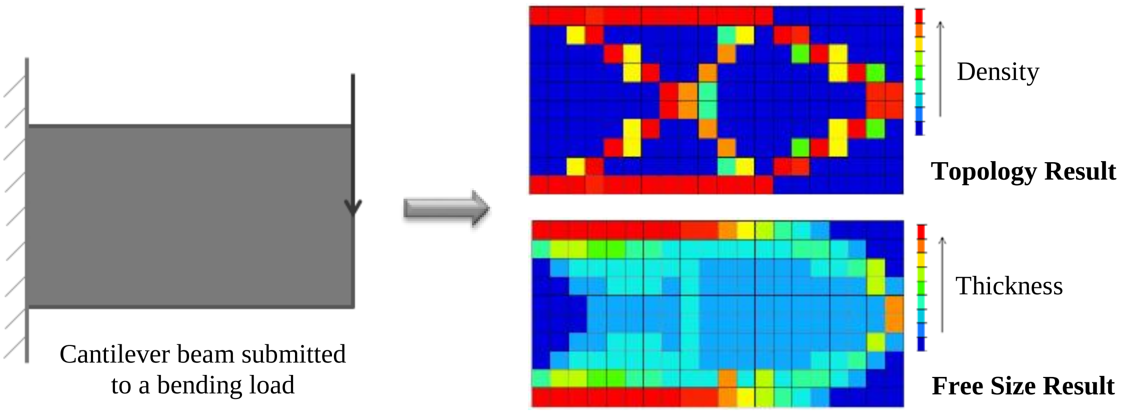

Figure 3: Topology versus Free Size Optimization Results

Since typical airframe composite structures made of laminates are most of the time simulated with 2D FEMs, methodologies presented in the following chapters are based on Size, Shape and Free Size optimization techniques. All these solutions based on FEMs follow an iterative process to resolve the optimization problem:

1. FEM analysis with the defined initial conditions.
2. Response screening. The optimization solver identifies and retain only the responses which are guiding the optimization, that is, the objective and constraints which are close to be violated. This response reduction is performed to reduce the problem size and consequently the computational cost.
3. Proposal of new designs to be evaluated according to the optimization algorithm selected by the user (gradient based, surface response based, genetic…).
4. FEM Analysis of new proposed designs.
5. Convergence criteria. The optimization solver determines if the convergence criteria are satisfied or not. If yes the optimization analysis ends. If not, go back to step 2.

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3. Composite Optimization Methods

Structural optimization can be applied at different levels. From optimization studies which purpose is to find an optimum architecture at aircraft level or MDO [3] (for example how many spars should define the substructure of a multipsar wing) up to the studies whose objective is the sizing single parts. As explained during the introduction, structure optimization usage has increased during the last years becoming one common tool for non-expert engineers in this discipline. The application field of the methods described in this paper is defined by the typical sizing analyses performed by stress engineers, mainly in linear regime. For this reason, these optimization methods have been developed within FEM solutions, well known by stress engineers, using as long as possible reference optimization solvers within the company. Complex optimization analyses which may involve different disciplines (dynamics, aerodynamics…) are not the scope of these methods remaining under the responsibility of expert optimization engineers.

3.1 Altair 3 Phases Method

The application within Airbus of this method is mainly based on the Altair proposed methodology for composite structures made of laminates [4]. In this chapter an application example of this methodology is presented as well as the modifications and extensions performed by Airbus to adapt the method to specific company needs. This method is based on a three phases approach, being the output of each phase the input of the following one up to complete the process. At the end of the process a laminate distribution is obtained along the composite structure with defined stacking sequences in line with manufacturing constraints imposed by the engineer. Hereafter a brief summary of each phase is presented.

1. Phase I. In this phase, applying a free size optimization, ply patterns which must conform the final laminates are provided. These ply patterns are obtained by each ply orientation present in the laminate (for example in a laminate made by tapes, ±0º, 45º and 90º).
2. Phase II. In this phase, applying a size optimization, the final number of plies is obtained according to the patterns previously defined. Therefore, at the end of this phase the thickness values along the composite structure are determined.
3. Phase III. In this phase, the plies previously defined are reordered in order to meet specific stacking sequence rules to obtain a final design which can be manufactured.

Gradient based optimization algorithms are automatically selected by the Altair structure optimization solver, OptiStruct, along the three phases depending on the number of constraints and design variables. Mainly SQP and MDF algorithms are used by the solver.

This three phase method is further explained with its application on a real aeronautic structure, the composite skins of a multispar wing.

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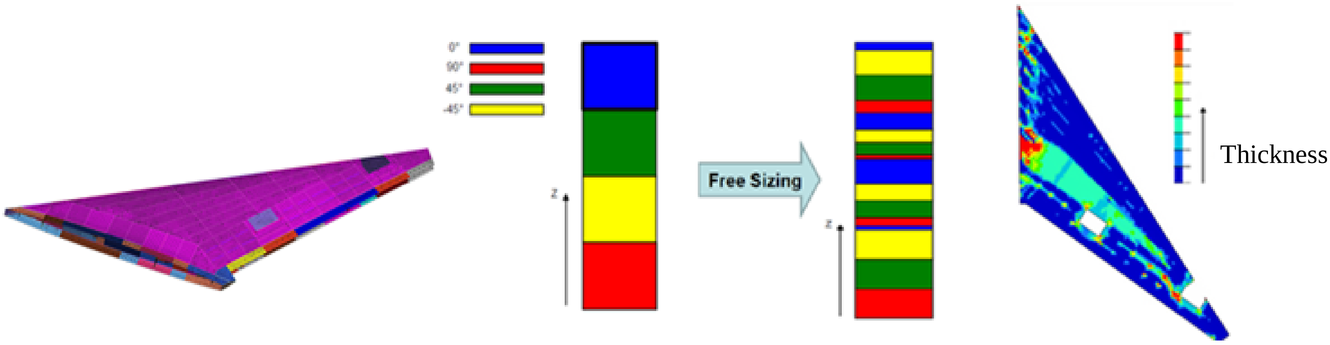
Phase I

The ply patterns are automatically generated by the free size optimization. These patterns, in a similar way that a topology optimization, provide the engineer with the main load paths within the structure. Figure 4 shows how the input of this phase must be defined and the results obtained at the end of the phase.



Input: One property along wing skins containing possible ply directions

Output: Thickness Distributions generated by the new ply patterns per orientation

Figure 4: Phase I Scheme

Results show a clear load path within the wing skins, this thickness distribution is consistent with engineering experience. The load path identified by the optimization is aligned with the wing-fuselage bending fitting which represents the main interface between the fuselage and the wing, that is, the main load transfer point.

Since the main purpose of this phase is the identification of the main load paths within the structure and the consequent extraction of the ply patterns, this thickness map distribution must not be understood as definitive as the final sizing is performed in Phase II. For this reason the optimization set up of this phase must be focused in searching the stiffest concept, delaying the application of typical sizing constraints as strain, buckling… to the Phase II. However specific composite manufacturing constraints can be imposed since Phase I to guide the complete optimization process to a result which meets the specific composite manufacturing constraints. The following manufacturing constraints, which are propagated to following phases, can be applied at this phase.

- Maximum and minimum allowed thickness along the composite domain.
- Ply Percentage. Maximum and minimum allowed thickness per ply orientation within the laminate.
- Ply balance. This constraint allows make equal the thickness value of two different ply orientations. Typically is applied to balance ±45° orientations.
- Ply drop off. By this constraint ply drop off rules can be implemented.

Phase II

Phase I automatically generates at the end of the free size optimization a new FEM which constitutes the input for the Phase II set up. However, before starting the sizing optimization in this phase, the engineer must perform an interpretation exercise over the output provided by Phase I. Ply patterns are defined by set of elements which come from the free size optimization, reason why they must redefined to obtain consistent ply patterns. Figure 5 shows this interpretation exercise and the resulting ply patterns for all ply orientations to be used during the size optimization.

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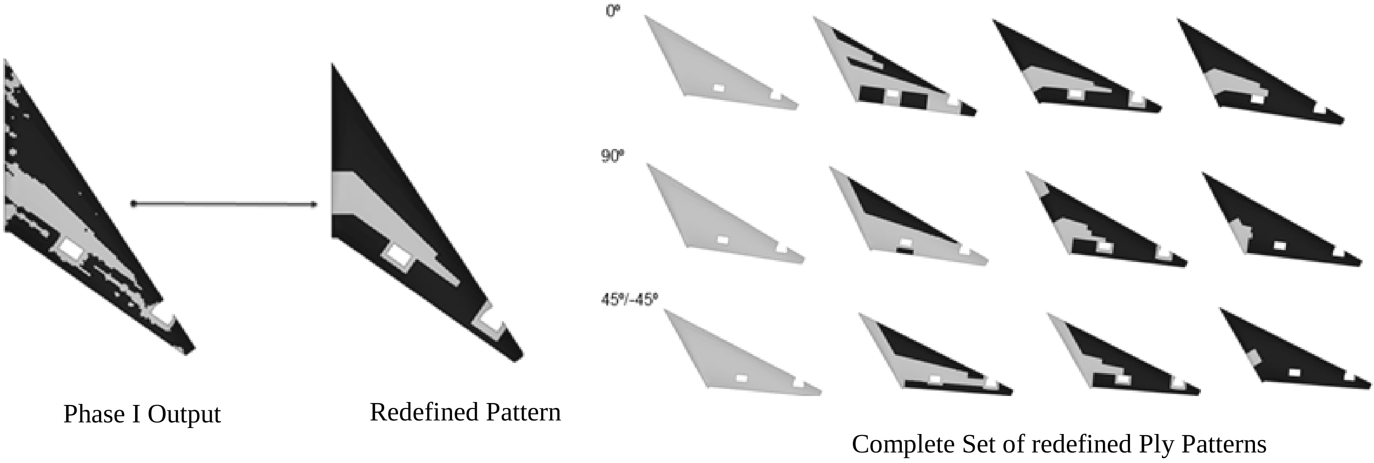

Figure 5: Ply Patterns Interpretation

Since the objective of this phase is to perform the sizing (minimizing the mass) of the composite structure, the constraints to achieve this goal are defined in this phase. Composite integrity can be assured by the application of different failure models (maximum strain, Tsai-hill, Hoffmann…), buckling and stiffness constraints. Manufacturing constraints defined in Phase I are propagated to this phase but a new manufacturing constraint may be added. Ply thickness can be imposed forcing the size optimization to provide a final thickness map which must be multiple of the ply thickness desired for the laminate.

Figure 6 shows a Phase II scheme and the result obtained at the end of this phase.

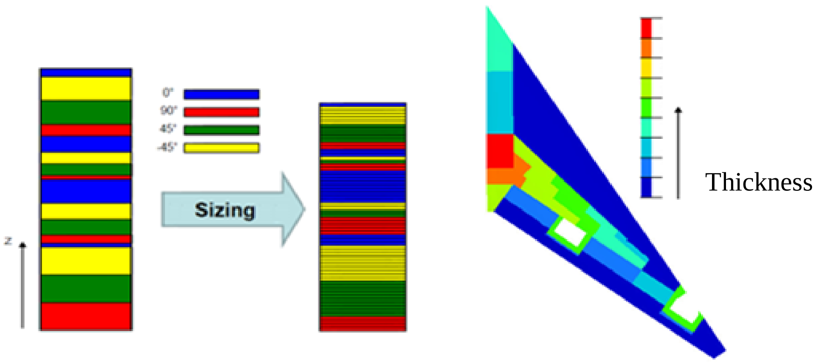

Figure 6: Phase II Scheme

Phase III

As observed in Figure 6, the result at the end of the Phase II is a well-defined thickness map made of plies following the patterns obtained in Phase I. However the laminate does not fulfil the typical stacking sequence rules used in the aeronautic industry for composites made of laminates. Moreover, since the mechanical properties of the laminate are dependent of the stacking sequence, the composite structure integrity is not guaranteed yet. In Phase II, to perform the size optimization, the optimization solver ignores the stacking sequence by the use of the membrane stiffness matrix for both, membrane and bending calculations. This simplification allows progressing in the optimization process but the engineer must be aware about the assumptions performed by the method and the derived limitations.

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During Phase III the optimization solver attempts to find and optimum stacking sequence, reordering the plies obtained an the end of Phase II, to meet the structural constraints imposed during the optimization process and adding the mentioned stacking sequence rules. The following stacking sequence rules are available in this phase.

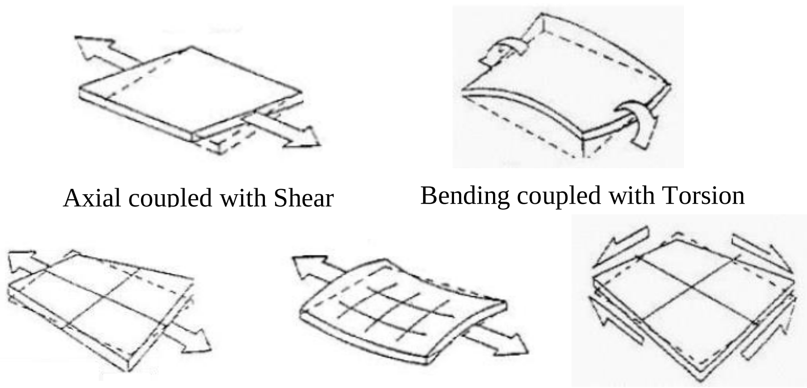
- Maximum number of plies with the same orientation stacked consecutively
- Pairing plies of different orientations. This constraint is typically used to pair ±45º plies
- Definition of a constant stack sequence for the extreme plies of the laminate.
- Definition of a constant stack sequence for the laminate core.

In this phase there is no mass evolution during the optimization and therefore the objective of this optimization step must be the increment of the structure stiffness while meeting strength and discussed manufacturing constraints.

Airbus Modifications over the 3 Phases Altair Method

One of the main advantages of composite structures is derived from the design freedom to customize the laminate mechanical properties according to loads applied on the structure. However, to assure a good structural performance, Airbus has developed along the years own specific stacking sequence rules which not always can be replicated by the default 3 Phases Altair Method.

As appointed before, stacking sequences are designed by Airbus depending on the type of element (skin, spar, rib, stringer…) and the associated loads applied. However, in general, symmetric and balanced laminates (same number of ±45º plies) are desired to obtain laminates with a high level of orthotropy. The main advantage of this type of laminates is the capability to minimize coupling load effect on composite structures. Figure 7 shows the coupling load effects that the specific Airbus stacking sequence rules attempt to minimize.



In plane loads coupled with out of plane effects (bending or torsion)

Figure 7: Load Coupling Effects on Laminates

Even if the specific stacking sequence rules developed by Airbus cannot be reproduced by the Phase III, the output at the end of Phase II represent valuable information for the laminates generation according to the mentioned rules. The engineer disposes for each zone of the structure the thickness and the percentage, per ply orientation, needed for the laminate. In Airbus the availability of a laminate catalogue, in line with the specific stacking sequence rules, is frequent. In this case the engineer can directly insert the laminate coming from this catalogue replacing the laminate, with the same thickness, obtained by the optimization process. Experience with this practice provides the following conclusions.

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- If manufacturing constraints imposed in Phase I are derived from the information available in the laminate catalogue, strength and stiffness results should not be significantly impacted by the replacement using the catalogue laminates. This conclusion is valid as long the composite structure is not submitted to significant bending loads due to the simplification performed in Phase II ignoring the stacking sequence.

- Catalogue laminates are designed for each specific structural element. Therefore, laminates to be used for skins are different to the ones used for ribs, spars… These laminates are designed to work in the most optimum way according to the load type that the structure must withstand. For this reason, commonly, better results (higher strength reserve factors, stiffness increment) arise when replacing the laminates obtained at the end of Phase II by the catalogue laminates.

Additional Phase. 0º Optimum Orientation.

Typically, in preliminary design phases, one parameter must be defined for composite wing skins like the ones showed in the example used to describe this method. This parameter corresponds with the 0º ply orientation which is used as reference to build up the laminates. Based on engineering experience this orientation is usually defined by a main wing substructure element. In this case the rear spar marked this orientation. An additional optimization analysis was carried out to find out if a different orientation could improve the wing performance by increasing the stiffness. Figure 8 shows the result of this optimization which revealed that a 9º clockwise rotation generated a global wing stiffness increment of 5%.

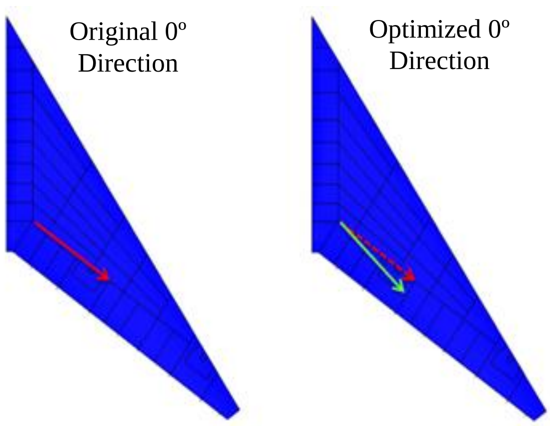

Figure 8: 0º Ply Orientation Optimization Result

Altair 3 Phases Method. Summary and Application Field

To help the engineer to decide when this method should be applied according to Airbus experience, strengths and weaknesses are collected hereafter.

Strengths

1. This method covers the complete optimization process. From a conceptual design phase, supported by the free size optimization, up to a detailed design phase carried out by the size optimization and rearrangement of the stacking sequence. Even though only the first two phases are applied, the optimization freedom allowed and hence the potential structure performance improvement is major than the other two methods to be described in the following chapters.

2. The process is fully guided by the FEM pre/post processors of Altair. Inputs for phases II and III are automatically generated by the optimization solver requiring few set up activities by the engineer.

3. Automatic manufacturing constraint generation by the optimization solver.

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Weaknesses

1. Very high numbers of design variables needed for Phase I. Depending on the FEM size and number of load cases the computational cost may be very high.

2. Not advisable if significant bending loads are applied to the composite structure. The simplification used by the method to ignore the stacking sequence during phases I and II may drive the optimization to not feasible or robust designs.

3. Stacking sequences generated by the method are in general not fully compatible with Airbus stacking sequence rules. Replacement of Phase III is required in most of the cases.

Due to previous detected strengths and weaknesses, Airbus considers this composite structure optimization method as the most suitable one when:

- The optimization target is a composite panel of large dimensions (wing skins, wind turbine blades…) to be submitted to a deep optimization analysis (covering conceptual and detailed design phases).

- The optimization is applied only to the composite structure. Since Phase I is only dedicated to obtain the ply patterns of the composite structure, the addition of design variables applied to metallic parts in Phase II may drive the optimization analysis to non-global optimum between metallic and composite parts.

- No significant bending loads directly applied to the composite structure.

3.2 Zone Based Method

Method Description

This method and the last one to be presented follow a zone based approach. This approach means, unlike the previous discussed method, that the engineer must decide the constant thickness zones in the composite structure beforehand. Therefore the design freedom provided to the optimization analysis is lower and as a consequence the performance improvement is also reduced. However, there are many cases in which the size of the composite structure to be optimized or the structure configuration already imposes these constant thickness zones. In these cases, the benefits of using the full 3 Phases method do not compensate the computational costs and engineering effort derived from the previous method.

Other cases in which these methods may result more suitable corresponds to studies in which detailed designs are not needed yet, for example, preliminary design phases in which an indicative weight is searched.

The application of this method results simple for the stress engineer, a stack per constant thickness zone must defined. This stack must contain the ply orientations which must build the laminate (for example in a laminate made by tape, ±0º, 45º and 90º). Using Size optimization technique the initial thicknesses per ply orientation in each zone are modified up to the optimum ones. For this method gradient based optimization algorithms are also recommended due to the quick convergence provided and easiness to be implemented in FEMs. Figure 9 shows a scheme of this optimization method.

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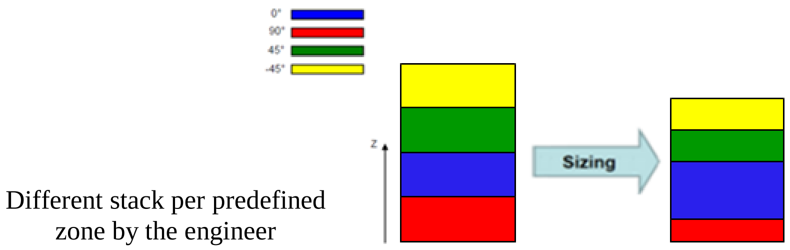

Figure 9: Zone Based Method. Optimization Scheme

Once concluded the optimization analysis the situation is similar to the previous method at the end of Phase II. The engineer must use the information provided for each zone, that is, total and per ply orientation thicknesses to build up new laminates to perform the final check stress of the composite structure. The main complexity of this method is the manual definition of the manufacturing constraints that must be imposed before running the optimization. These manufacturing constraints are essential to guide the optimization analysis to a design which can be manufactured.

Selected optimization solver, based on FEMs, used with this method must allow the engineer to stablish functions which define relations between the different design variables (ply orientation thicknesses) to stablish the manufacturing constraints. This type of relations is not always available for any optimization solver. In this case, again, the Altair structure optimization solver OptiStruct is chosen to support this method. At least the following user-defined manufacturing constraints should be stablished, per zone, to guide the optimization.

- Maximum and minimum allowed thickness.
- Ply Percentage. Maximum and minimum allowed thickness per ply orientation within the laminate
- Ply balance. This constraint allows make equal the thickness value of two different ply orientations. Typically is applied to balance ±45° orientations.
- Ply thickness to force the final thickness result to a multiple of this value.

Figure 10 shows an application example of this method. A hybrid structure (metal stiffeners and composite panel) is submitted to optimization using as design variables the thicknesses of the predefined composite zones and the metal stiffeners dimensions (thicknesses, height and head width). In total 29 design variables are defined (Each colour in the optimization model represents a different predefined constant thickness zone). Strength and buckling constraints are imposed trying to minimize the component mass.

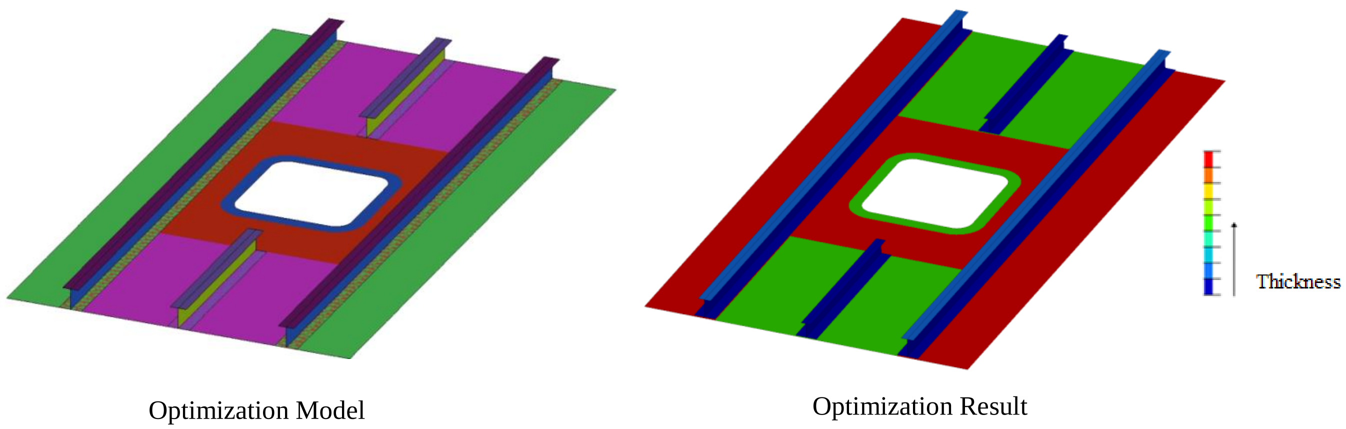

Figure 10: Zone Based Method. Optimization Example

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Zone Based Method. Summary and Application Field

To help the engineer to decide when this method should be applied according to Airbus experience, strengths and weaknesses are collected hereafter.

Strengths

1. Compatible with optimization of composite and metal parts. Since the conceptual optimization is suppressed in this method, no risk exists of finding a non-global optimum between parts made of different materials. All design variables are considered by the optimization algorithm at the same time and with the same weight.

2. Same rationale applies to the use of Size and Shape design variables. If shape design variables are defined in the optimization analysis, unlike the previous method, they are considered at the same time and with the same weight than size design variables. Therefore, any dimensions of metallic and composite parts can be used to optimize structures with presence of different materials.

3. Less complex than 3 Phases Method.

4. Lower computational cost since the method is based on only one optimization analysis, instead of 3, and with a reduced number of design variables.

Weaknesses

1. Generation of laminates based on the information provided is required. Therefore a final analysis is needed since the output from the optimization cannot be used as check stress.

2. Not advisable if significant bending loads are applied to the composite structure. The simplification used by the method to ignore the stacking may drive the optimization to not feasible or robust designs.

Due to previous detected strengths and weaknesses, Airbus considers this composite structure optimization method as the most suitable one when:

- The structure to be optimized does not present a high degree of freedom reason why the constant thickness zones can be stablished beforehand.

- The structure to be optimized presents composite and metallic parts.

- The optimization objective is not as ambitious as for the 3 Phases Method. In these cases the complexity of the 3 Phases method might not compensate its application.

- No laminate catalogue is available for the structure to be analysed.

- No significant bending loads directly applied to the composite structure.

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3.3 Zone Based Method with Direct Laminate Implementation

Method Description

Methods previously discussed revealed the two main issues to apply optimization to composite structures. The first issue, already appointed in the introduction, is related with the specific manufacturing constraints that composite structures must fulfil. The second issue lies on the difficulty to skip the stacking sequence influence on the laminate mechanical properties during the optimization. The intention of this method is to overcome both issues removing the need to build up new laminates based on the thicknesses for the different ply orientations obtained by the optimization analysis.

As mentioned in previous chapters, it is common to dispose of laminate catalogues which are specifically designed for each structural element type depending on the type of loading to which the structural element is submitted. This method attempts the direct implementation of these laminates into the zones predefined by the engineer. Therefore, the two main issues identified so far are automatically resolved as the manufacturing constraints and real stacking sequences are embedded into the design variables.

The set up for this optimization method requires using a structure optimization solver which allows the use of conditional links and algorithms capable to work with discrete design variables. Figure 11 shows a scheme of this optimization method.

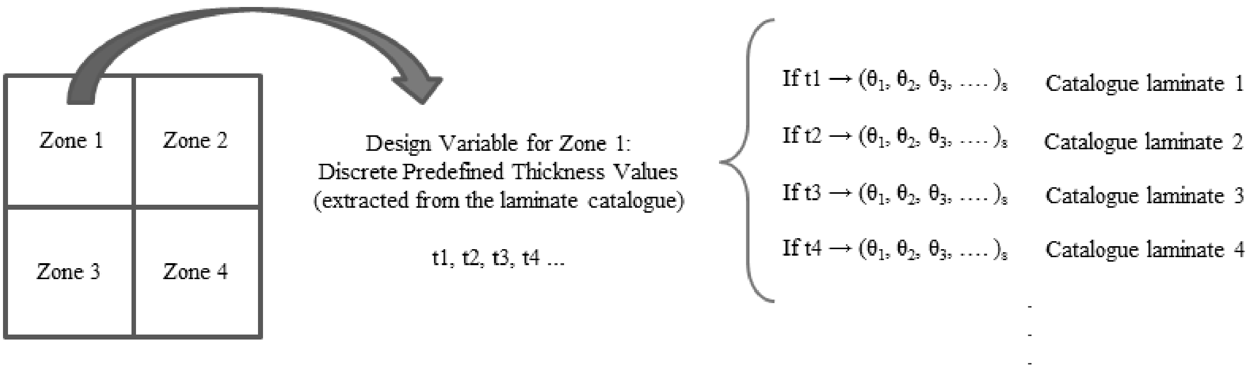

Figure 11: Zone Based Method with Direct Laminate Implementation Optimization Scheme

Zone based Method with Direct Laminate Implementation. Summary and Application Field

To help the engineer to decide when this method should be applied according to Airbus experience, strengths and weaknesses are collected hereafter.

Strengths

1. Compatible as previous method with optimization problems with presence of composite and metallic parts

2. Compatible as previous method with Size and Shape design variable to allow the engineer to use any structure dimension as design variable

3. No need to build new laminates to perform the final validation analysis. The output from the optimization can be directly used.

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Weaknesses

1. Laminate catalogue is needed. In absence of this information the engineer must generate it to be able to use this method.

2. More complex to set up and higher computational cost than Zone Based Method. Optimization algorithms with capability to work with discrete design variables make more costly the optimization convergence.

Due to previous detected strengths and weaknesses, Airbus considers this composite structure optimization method as the most suitable one when:

- The structure to be optimized does not present a high degree of freedom reason why the constant thickness zones can be stablished beforehand.

- The structure to be optimized presents composite and metallic parts.

- Laminate Catalogue exists for the type of composite structure to be analysed.

- Significant bending loads must be withstood by the composite parts.

4. Conclusions

First applications of structure optimization became a reality within the aeronautic industry twenty years ago. Since then, the use of optimization techniques has grown and expanded from very specific structure issues analyzed by expert engineers integrated into optimization centers to a wider structure analyses and engineering community. This optimization expansion use has been mainly focalized for metallic structures, remaining the composite structure on expert mode due to their inherent complexity as a consequence of specific manufacturing constraints.

The intention of the 3 methods discussed in this paper is to provide stress engineers with similar tools to optimize composite structures made of laminates as the well-known tools for metallic structures. Optimization analyses, following the optimization driven design philosophy, but always in combination with the engineering experience, has demonstrated to be a powerful mean to generate light weight aeronautic structures.

Since the Altair 3 Phases method is the only one which covers the complete optimization process (from conceptual up to detail optimization) constitutes the preferred method when the optimization capabilities must be exploited to obtain the best composite structure performance. In cases in which this optimization potential cannot compensate the complexity associated to this method, the Zone Based Methods may result more suitable and easy to set up for the engineer. However, as discussed, none of the methods is free of drawbacks. For this reason, according to the structure to be optimized (complexity, type of loads, optimization objective…) the engineer must evaluate and decide which method is the most suitable in each case.

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6. Glossary

2D	–	2 Dimensions
FEM	–	Finite Element Model
MFD	–	Method of Feasible Directions
SIMP	–	Solid Isotropic Material Penalization
SQP	–	Sequential Quadratic Programming