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Topology and Size Optimization of Composite Ply Cargo Door

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Abstract

Structural optimization has seen accelerated deployment throughout all industries in the past decade, largely due to the recognition that tremendous efficiency gain can be achieved at concept design stage through topology optimization. For composite laminate design a three-phase optimization process is used. The target of the first phase is the material distribution in terms of orientation and thickness. This is achieved through topology optimization where thickness of each 'super-ply' of a unique fiber direction is allowed to change freely throughout the structure. As a result thickness contour of each fiber orientation is obtained. A discrete interpretation of the thickness contour results in concept design of ply layout and thickness. Then in Phase-II the interpreted ply-based structural model is further optimized under all design constraints with discrete design variables representing the number of plies of each ply patch. During Phase-III, ply stacking optimization is performed to refine the design according to detailed manufacturing constraints. All manufacturing constraints are considered throughout all three optimization phases. Such requirement would translate into percentage requirement during Phase-I and II so that a balanced distribution of fiber orientation is achieved to allow feasible stacking during Phase-III. The three-phase optimization process is illustrated in this paper. A unique modeling technique developed in conjunction with the optimization process is the ply-based finite element analysis model where ply entities are defined as sets of elements. Then ply layup is specified by a stack definition. In the following sections the procedure is demonstrated for one of the preliminary configurations developed for the composite cargo door.

1. Introduction

Optimization [1] can be defined as the automatic process to make a system or component as good as possible based on an objective function and subject to certain design constraints. There are many different methods or algorithms that can be used to optimize a structure. OptiStruct is implemented algorithms based on gradient method.

1.1 Conventional versus optimum design process

It is a challenge for engineers to design efficient and cost-effective systems without compromising the integrity of the system. The conventional design process depends on the designer's intuition, experience, and skill. This presence of a human element can sometimes lead to erroneous results in the synthesis of complex systems as shown in figure 1.
Scarcity and the need for efficiency in today's competitive world have forced engineers to evince greater interest in economical and better designs. The computer-aided design optimization (CADO) process can help in this regard as shown in figure 2.

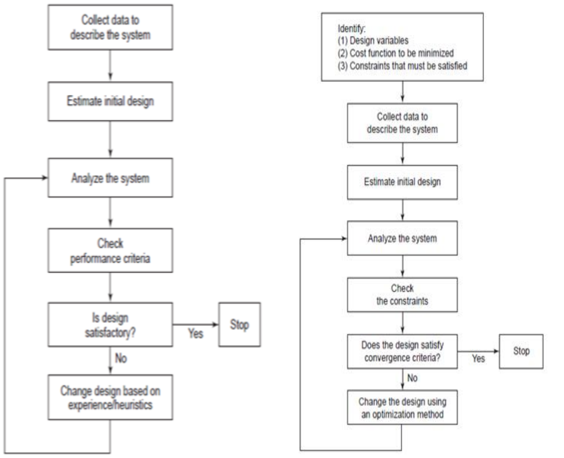


Figure 1. Conventional vs. Optimum design process

1.2. Optimization Definitions [2]

- *Topology*: Topology optimization is a mathematical technique that optimized the material distribution for a structure within a given package space

- *Topography*: Topography optimization is an advanced form of shape optimization in which a design region for a given part is defined and a pattern of shape variable-based reinforcements within that region is generated using OptiStruct.
- *Free Size*: Free size optimization is a mathematical technique that produces an optimized thickness distribution per element for a 2D structure.
- *Shape*: Shape optimization is an automated way to modify the structure shape based on predefined shape variables to find the optimal shape.
- *Size*: Size optimization is an automated way to modify the structure parameters (Thickness, 1D property, material properties, etc…) to find the optimal design.
- *Gauge*: Gauge optimization is a particular case of size, where the DV are 2D props (Pshell or Pcomp)
- *Free Shape*: Free shape optimization is an automated way to modify the structure shape based on set of nodes that can move totally free on the boundary to find the optimal shape.
- *Composite shuffle*: Composite shuffle is an automated way to determine the optimum laminate stack sequence. Design Variables (DVs) are the plies sequence of stacking. It is used for composite material only defined using Pcomp (G) or Pcomp (P).

1.3. Optimization Terminology

- *Design Variables*: System parameters that are varied to optimize system performance.
- *Design Space*: selected parts which are designable during optimization process. For example, material in the design space of a topology optimization.
- *Response*: A function of the design variable (e.g. Mass, stress, displacement and etc.) used to measure the performance of a part.
- *Objective Function*: Any response functions of the system to be optimized. The response is a function of the design variables. Ex. Mass, Stress, Displacement, Moment of Inertia, Frequency, Center of Gravity, Buckling factor, and etc.
- *Constraint Functions*: Bounds on response functions of the system that need to be satisfied for the design to be acceptable.
- *Feasible Design*: One that satisfies all the constraints.
- *Infeasible Design*: One that violates one or more constraint functions.
- *Optimum Design*: Set of design variables along with the minimized (or maximized) objective function and satisfy all the constraints.

2. Topology Optimization

Topology Optimization [3] is a mathematical technique that produces an optimized shape and material distribution for a structure within a given package space. By discretizing the domain into a finite element mesh, OptiStruct calculates material properties for each element. The OptiStruct algorithm alters the material distribution to optimize the user-defined objective under given constraints.

OptiStruct solves topological optimization (sometime referred as *free-size optimization*) problems using either the homogenization or density method. Under topology optimization, the material density of each element should take a value of either 0 or 1, defining the element as being either void or solid, respectively.

Unfortunately, optimization of a large number of discrete variables is computationally prohibitive. Therefore, representation of the material distribution problem in terms of continuous variables has to be used.

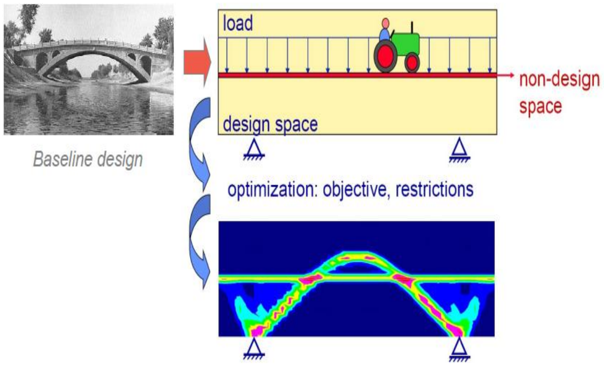


Figure 2. Topology optimization process

3. Size Optimization

The purpose of composite sizing optimization [4] is to create design concepts that utilize all the potentials of a composite structure where both structure and material can be designed simultaneously. By varying the thickness of each ply with a particular fiber orientation for every element, the total laminate thickness can change ‘continuously’ throughout the structure, and at the same time, the optimal composition of the composite laminate at every point (element) is achieved simultaneously. At this stage, a super-ply concept should be adopted, in which each available fiber orientation is assigned a super-ply whose thickness is free-sized.

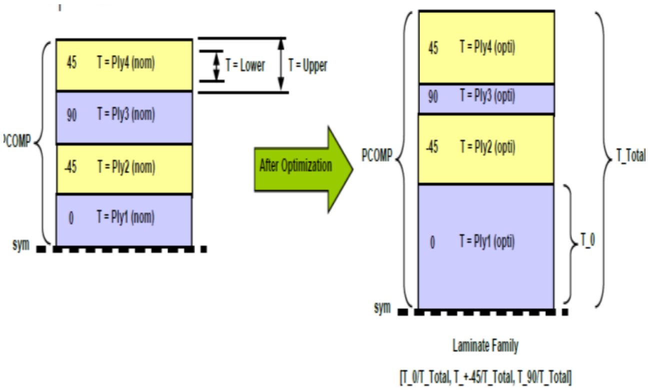


Figure 3. Free size optimization

4. Optimization of a Composite Cargo Door

4.1 Problem Description

An aircraft composite cargo door [5,6] is subjected to pressure loads and is fixed on the periphery. The orthotropic material is already defined in the model.

1. *Concept Design:*

To optimize the door for optimum Composite Ply Drop Off [7,8] using free size optimization (topological optimization) by using ply orientations 0, 45/-45 and 90, each of 3 mm super ply thickness (Total Laminate = 12 mm thick).

2. *Design Fine Tuning:*

- Also optimize the thickness of each ply (Composite Size) and the stacking sequence (Shuffling) of all the plies in the laminate. Compare designs with at least 2 other stacking sequences by fixing core/cover or max successive plies.
- Maximum Allowable Displacement is 12 mm.
- Manufacturable ply thickness = 0.25
- Minimum Laminate Thickness = 9 mm
- 45/-45 plies to be balanced

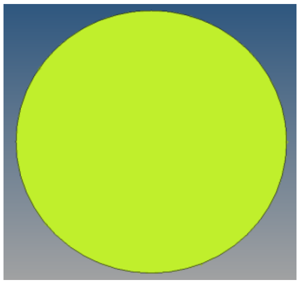


Figure 5. Model of a cargo door

4.2 Material Description

Table 1. Composite material data

Material	Carbon fiber T800
Resin	Epoxy Resin 912
Young’s modulus,E1	1.5e5 N/mm^2
Young’s modulus,E2	7000 N/mm^2
Rigidity modulus,G12	5000 N/mm^2
Poisson ratio	0.3
Density	1.6e-6 kg/mm^3

4.3 Property Definition

Table 2. Plies property

Ply No.	Thickness (mm)	Orientation (in deg)
Ply 1	3	0
Ply 2	3	45
Ply 3	3	-45
Ply 4	3	90

4.4 Finite Element Model (FEM) and Boundary Conditions (BCs) [9]

Boundary Conditions: All DOF is Constraint at Periphery and pressure load of 0.0623 MPa is applied.

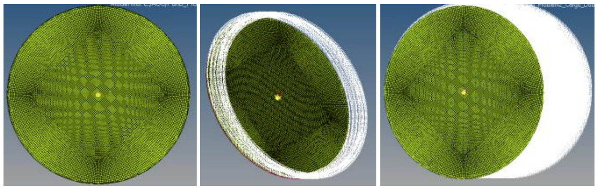


Figure 6. FEM Model and BCs

5. Phase I-Topology Optimization

The target of the first phase is the material distribution in terms of orientation and thickness. This is achieved through topology optimization where thickness of each 'super-ply' of a unique fiber direction is allowed to change freely throughout the structure. As a result thickness contour of each fiber orientation is obtained [10]. A discrete interpretation of the thickness contour results in concept design of ply layout and thickness.

Optimization objective is to

- Minimize the mass
- Maximum Displacement on center ≤ 12

Optimization setup

- Design Variables: Door ply thickness Ti for each element with manufacturing constraints balanced ±45° plies.
- Design Response: Mass, displacement and compliance(inverse of stiffness)
- Optimization Constraints: Mass with upper limit of 115 kg and displacement with upper limit of 12 mm
- 'Ti' varies continuously between 0 and Ti-initial
- If no stiffness is needed for 90°Ply in element X, the variable T90° will reduce or become zero.
- Additional plies with different angels can also be used.
- Objective is to minimize the compliance (i.e. displacement)

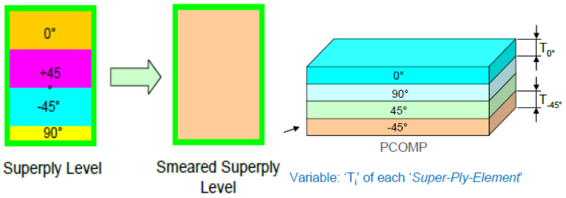


Figure 7. Optimization setup

5.1 Results

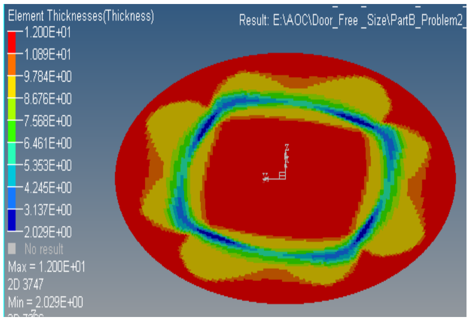


Figure 8. Total element thickness distribution

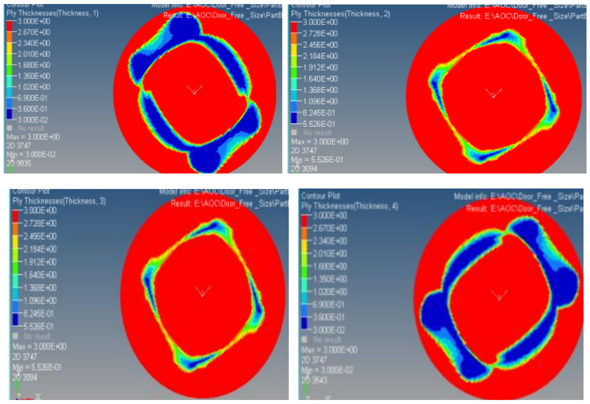


Figure 9. Ply thickness distribution (0, 45,-45 & 90 degrees)

6. Phase 2 – Design Fine Tuning (Size Optimization)

In the second design phase, a size optimization is performed to fine tune the thicknesses of the optimized ply bundles from Phase 1. To ensure that the optimization design meets the design requirements, additional performance criteria on natural frequencies and composite strains are incorporated into the problem formulation. The optimization setup is also modified to factor in these additional performance targets, among others.

The following is the modified optimization setup [11]:

- Design variables is ply thicknesses, which have been defined in the topology optimization from Phase 1
- Objective is to minimize the total designable volume.
- Constraint: Maximum Allowable Displacement is 12 mm with manufacturable ply thickness of 0.25 mm.
- Repeat the rest of the steps similar to phase 1.

6.1 Results

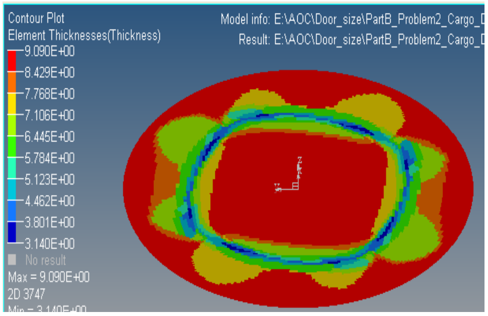


Figure 10. Elemental thickness

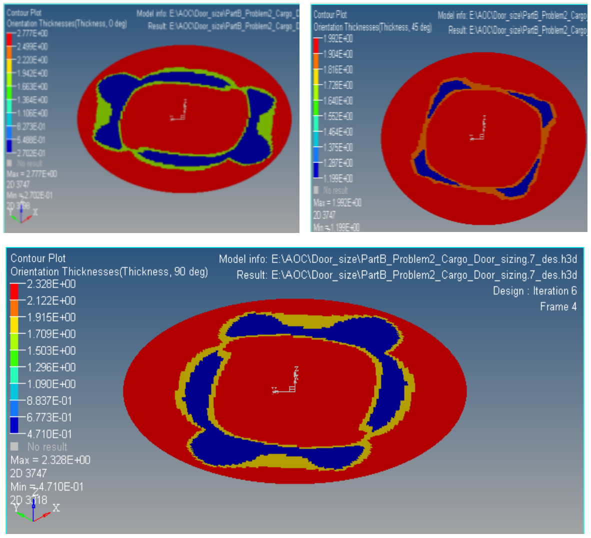
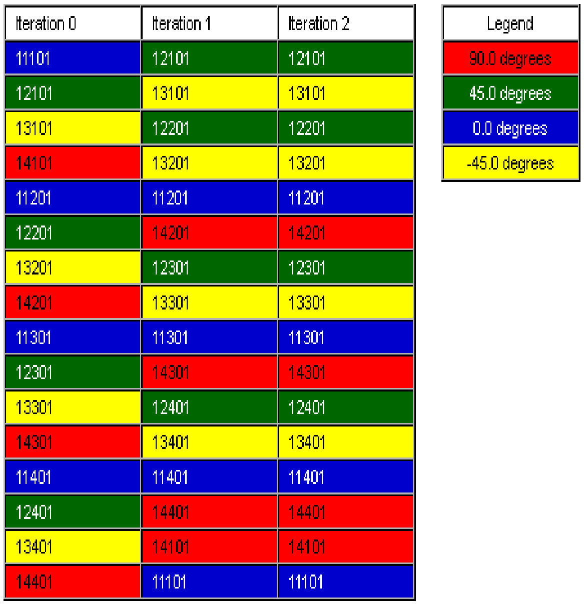


Figure 11. Size optimization results per fiber orientation (0, +45/-45 and 90 degrees)

7. Phase 3 – Ply Stacking Sequence Optimization

In this design phase, composite plies are shuffled to determine the optimal stacking sequence [12,13]. A DSHUFFLE card was created automatically during the sizing phase. Two manufacturing constraints will be added for the shuffling optimization.

7.1 Ply Stacking Sequence Optimization



Iteration 0	Iteration 1	Iteration 2
11101	12101	12101
12101	13101	13101
13101	12201	12201
14101	13201	13201
11201	11201	11201
12201	14201	14201
13201	12301	12301
14201	13301	13301
11301	11301	11301
12301	14301	14301
13301	12401	12401
14301	13401	13401
11401	11401	11401
12401	14401	14401
13401	14101	14101
14401	11101	11101

Legend
🟥 90.0 degrees
🟩 45.0 degrees
🟦 0.0 degrees
🟨 -45.0 degrees

Figure 12. Ply Stacking Sequence

7.2 Results

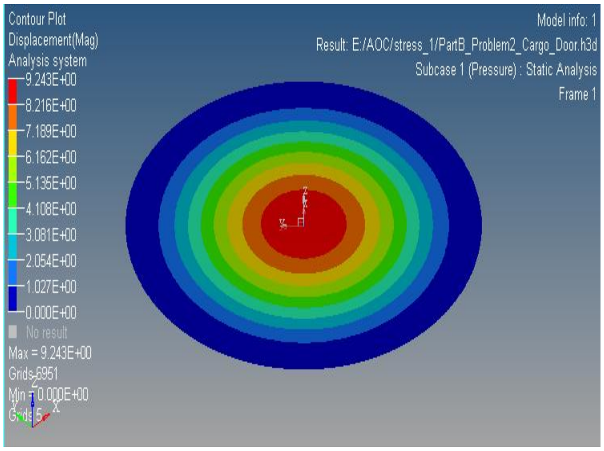


Figure 13. Initial contour displacement

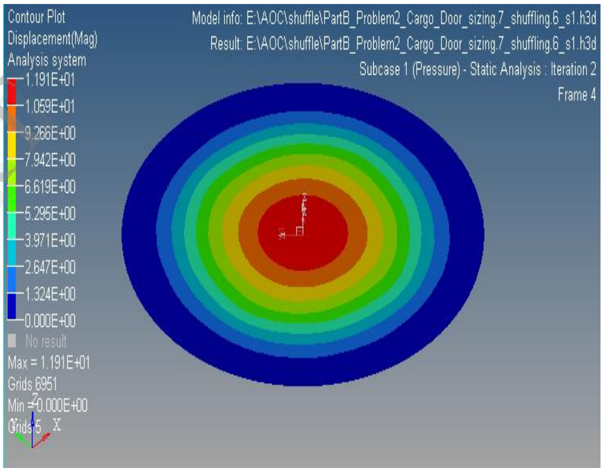


Figure 14. Final contour displacement

8. Conclusions

The following are the conclusions made:

- This paper introduces a unique and comprehensive process for design and optimization of composite laminates.
- The maximum displacement at center is 11.91mm which is less than allowable displacement 12mm.
- The final composite laminates thickness is 9.09 mm compared to 12mm initial thickness.
- The final mass of composite cargo door is 89.98kg

Free size optimization for composites allows a true concept level design synthesis of ply. A new PLY and STACK based modeling technique than simplifies laminates representation and facilitates the ply bundle sizing optimization followed by the stacking optimization makes the process unique.

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