ADVANCED OPTIMIZATION OF COMPOSITE STRUCTURES INCORPORATING STRENGTH, DAMAGE, ROBUSTNESS & RELIABILITY

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Keywords: composites, optimization, reliability, simulation

Abstract

This paper presents new simulation technology and methodologies related to the optimization of a composite component with a focus on robustness and reliability of the final as-built product. The optimization and analysis will take into account the strength of the structure, the detailed ply layup of the structure, the manufacturability of the part, as well as the damage tolerance of the structure. A composite winglet is used as the example for the design optimization and the Abaqus and Isight software products are utilized to take into account factors that are too often ignored by design methodologies used today.

1 Introduction

Optimization is the process of finding the best design for a particular goal while meeting the design requirements. For structural engineers this typically means finding the design that will minimize the weight of the part while still surviving the prescribed loads. In common practice this means performing a topology or geometry optimization (looking at changes in geometry, thicknesses, radii, etc.) to minimize weight while maintaining an allowable stress limit. Unfortunately, this is a very narrow and limiting view of optimization and can result in bad designs; designs that fail in the field.

The real goal of optimization is not to just lower the weight of a part, but also to create a part that is manufacturable. The real goal is not to create a design that just barely passes the critical stress criteria, i.e. has a margin of safety of 0.001; but that also is reliable in the field. The real goal should include manufacturability and reliability, and also robustness and cost (production cost and in-service costs).

This paper is going to demonstrate a methodology that allows engineers to expand how they perform optimization to account for reliability and robustness. A composite aircraft winglet will be used as the example model for the analysis (Figure 1).

Figure 1. Aircraft winglet used as the example for this methodology study.

2 Software Tools

Often engineers ignore factors like reliability and robustness, not because they are bad engineers, but because the software tools they are using are limited. Many of the optimization codes do not provide statistical optimization that allows engineers to account for variability in material properties and variability in manufacturability.

For this paper, the software product Isight from SIMULIA was utilized. Isight is a process automation and optimization framework code. Isight allows users to perform optimizations using one of several different algorithms, monte carlo simulations, Design of Experiments (DOE), design for six sigma, examination of reliability and robustness, as well as inclusion of performance and costs in the optimization [1]. The strength of Isight is shown as a schematic in Figure 2. Isight allows engineers to combine multiple routines to perform a broader and more realistic optimization. The product design can start with a Design of Experiments (DOE), then perform a traditional optimization to find a design that lies on the critical constraint boundary (red outlined dots), and then account for variability in material properties and manufacturing to examine the reliability of the product (red solid dots). Isight can then find an optimal design that is slightly away from the critical boundary to increase the reliability of the product; i.e., all products being produced will survive the in-service loads (solid green dots).

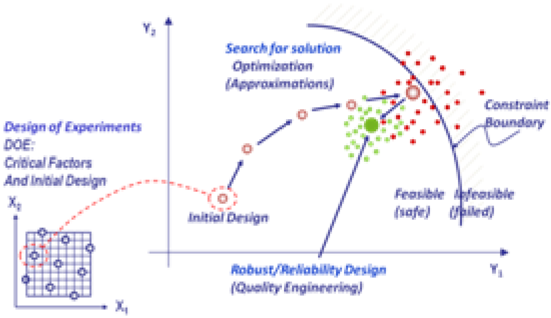

Figure 2. Schematic of optimization methodology including reliability and robustness.

The Isight software code does not perform the structural analysis. Isight uses components that allow users to embed other simulation codes and FEA codes that perform the structural analysis (or thermal, CFD, optical, or any other analysis). Isight has over 40 components that allow it to connect with various software products (including EXCEL, MATLAB, Nastran, Abaqus, and CFD codes). For this example problem, Abaqus was used to perform the structural analysis of the composite winglet [2]. The Abaqus component in Isight was utilized so that Isight drove the Abaqus analysis, and the user did not have to directly perform the Abaqus simulations.

3 Traditional Optimization

To highlight the limitations of "traditional" optimization methods, this paper will start by performing a "traditional" optimization and then extend it to examine reliability and robustness. The traditional optimization will examine a simplified composite winglet. The goal is to minimize weight whilst keeping the stresses in the composite below the critical level.

3.1 Analysis Model

The first step is to create the structural analysis model for the winglet. To create the finite element model (FEM), the geometry of this winglet was imported into Abaqus/CAE; the preprocessor and postprocessor for Abaqus. In Abaqus/CAE, the winglet was meshed, the material properties were defined, and a baseline composite layup was defined. The critical load case for this winglet is a pressure load. This pressure load was also defined in Abaqus/CAE. (Figure 3).

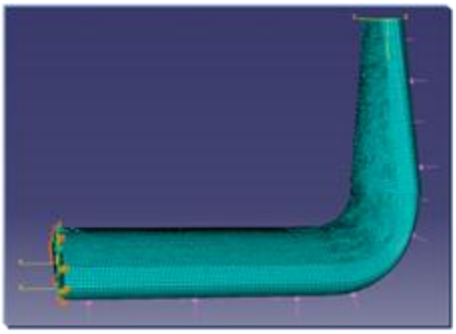

Figure 3. Winglet finite element model in Abaqus/CAE; mesh, boundary conditions, and pressure loads are shown.

3.2 Optimization Process

Isight is used to define the optimization process, variables, objectives and constraints. The Isight interface provides a workspace where users can drag-and-drop components or activities to define the process; or what is called the Sim-Flow (Figure 4). For this winglet, our Sim-Flow starts with an EXCEL component that contains our composite material database. The next step in the process is the Input Arrays component that modifies the composite layup, varying the number of plys and the ply angles. That step is followed by the Data Exchanger component that updates the Abaqus model file. And the final component is the Abaqus simulation.

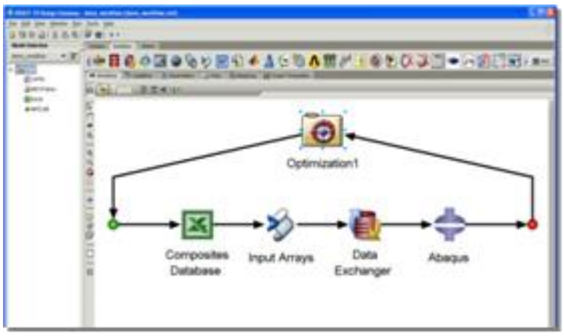

Figure 4. Isight interface shows the various components in the winglet optimization.

Once the Sim-Flow is created, the optimization parameters need to be defined. For this optimization, there are two defined objectives. The first objective is to minimize the number of plys. The thinking is that by minimizing the number of plys, we are also minimizing the weight of the part. The second objective is to minimize the Tsai-Wu failure index. For this objective, each ply layer of each element is evaluated during the simulation. A constraint is defined that the Tsai-Wu failure index must be below 1.0.

The design variables for this problem include varying the number of plys of the composites; from 2 plys to 5 plys. And also varying the angle of the plys; from -90 degrees to +90 degrees in discrete increments [-90 -45 -30 -15 0 15 30 45 90]. For the optimization, the user can choose a gradient method, pattern search, or exploratory techniques. For this problem, a genetic algorithm was utilized.

3.3 Optimization Results

The total number of possible designs that could be created from the variables listed above is over 64,000. Isight ran through 181 different designs in this optimization study; as guided by the genetic algorithm. The results from optimization studies can be viewed in several different ways in Isight.

Figure 5a displays the Tsai-Wu failure criteria for the various design iterations. All of the designs with values below 1.0 are passing designs (these are noted with black dots; failing designs are noted with red dots). Figure 5b displays the same information, but this time the vertical axis is showing the number of plys of the composite. From this view, we can see that there are no 2-ply designs that pass our stress criteria. There are several 3-ply and 4-ply designs that pass the criteria and all of the 5-ply designs pass the criteria.

Another way to view the results is to look at the Pareto Front (Figure 6). The Pareto Front is the curve that passes through the best design for the different number of plies. Isight also allows users to view the influence matrix, or the amount of correlation between the input variables and the output responses (not shown).

The final step in viewing and understanding the optimization results is to examine the results in the FEA postprocessor; in this case Abaqus/Viewer. Since both Isight and Abaqus are products from SIMULIA, they are linked together, and users can simply highlight a design iteration in Isight and automatically bring up the design results in Abaqus/Viewer for further post processing. Based on this optimization, the conclusion is that the 3 ply design is the best design. It is the lightest weight and it passes the Tsai-Wu failure criteria (Figure 7).

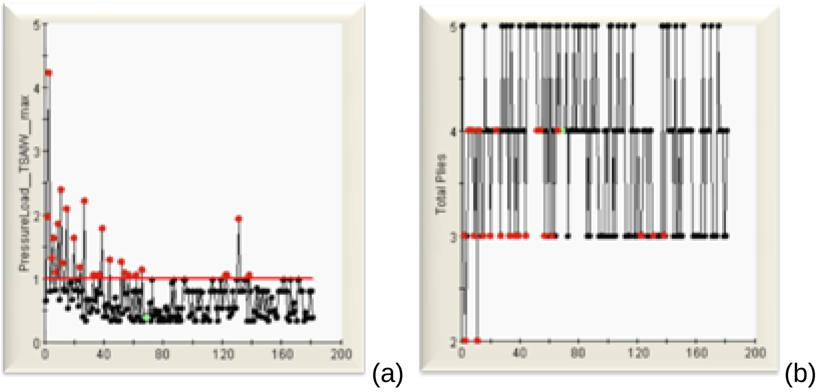

Figure 5. Results from Isight optimization; red dots denote designs that fail the Tsai-Wu criteria; x-axis is the design iteration number.

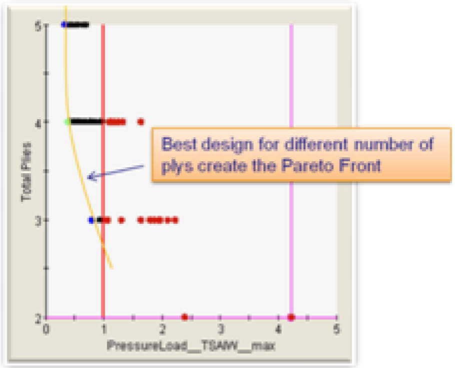

Figure 6. Results organized by number of plys and showing the Pareto Front.

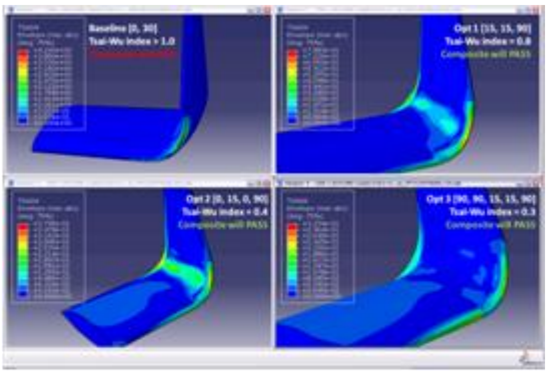

Figure 7. The best 2 ply, 3 ply, 4 ply, and 5 ply designs.

4 Realistic Optimization

Our traditional optimization led to the determination that the 3-ply design is the best design. But, is this really the best design? Is it robust? Is it reliable? With the optimization methodology performed in most design processes today ("traditional" optimization), robustness and reliability is not examined. Not accounting for real variability can result in real problems. This next section will examine variability in material properties and in manufacturability and determine how it affects our optimized design. The questions of reliability and robustness will be answered.

To examine the variability in inputs, a Monte Carlo simulation is performed. This Monte Carlo simulation evaluates the best 3-ply and 4-ply designs that were obtained from the optimization analysis. The Monte Carlo simulation is performed using statistical variations in inputs to examine the robustness and reliability of the designs. For this problem, variations in ply angle (+/- 10%), material properties (+/- 10%), and ply thicknesses (+/- 10%) were examined. For all of these variations, a normal distribution was assumed. 100 samples were analyzed.

4.1 Reliability and Robustness Results

From this simple examination, assuming small variability in material properties and manufacturing tolerances (ply angles), we can see that our traditional optimized 3-ply design, is a terrible design. The results from the reliability analysis show that there is a 13 percent probability of the winglets failing. This 3-ply design is not reliable. In comparison, the 4-ply design with the same amount of variation in inputs, is reliable. There is a zero percent probability of failures (Figure 8).

Another way to look at the difference in reliability of the 3-ply versus the 4-ply design is to plot them both on a scatter plot (Figure 9). The scatter plot clearly shows that the 4-ply design is more reliable (no points above the critical Tsai-Wu failure criteria). This plot also shows that the 4-ply design is more robust. There is more consistent performance between the different designs. This is evident by the reduced amount of scatter or variance in the output results. In other words, for the same amount of variance in the inputs, the 4-ply design has less variance in ouput; it is more robust.

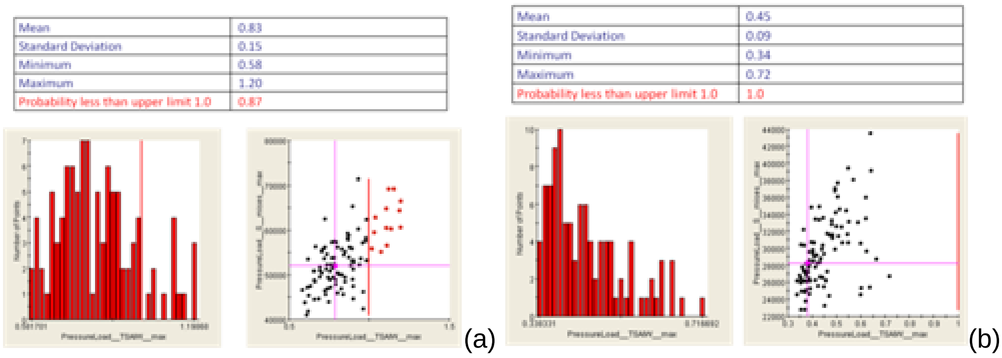

Figure 8. Reliability analysis of the 3-ply design shows a 13 percent probability of failure (a), while the Reliability analysis of the 4-ply design shows a 0 percent probability of failure (b).

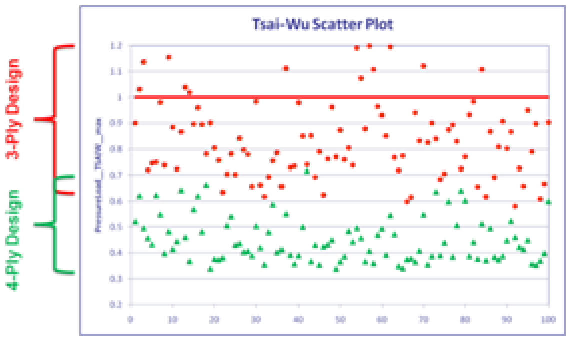

Figure 9. Scatter plot showing the robustness and reliability of the 3-ply and 4-ply designs.

5 Conclusions

This paper examined the optimization of a composite winglet and highlighted the fact that "traditional" optimization that neglects reliability and robustness studies can lead engineers to select non-optimal and simply 'wrong' designs.

Realistic optimization needs to account for factors such as variations in material properties and variations in manufacturing. Isight software from SIMULIA has been developed to enable this type of realistic optimization.

As a final note; this optimization and examination of reliability and robustness was performed as two separate parts. With Isight, it is trivial to nest Sim-Flows together so that the optimization loop incorporates the reliability study.

References

[1] Isight 5.7 user's manual. Dassault Systèmes; 2011.
[2] Abaqus® 6.11 Analysis user's manual. Dassault Systèmes; 2011.