Abaqus Technology Brief

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Composite Winglet Optimization for Reliability and Robustness

Summary

Optimization is widely accepted in product development and engineering. Advances in automated software and computing power make it possible to quickly and thoroughly explore design spaces in a rigorous manner.

Composite materials offer the potential for structures of lighter weight than their metallic counterparts. The stiffness and strength of a laminated composite structure depends directly on the ply stacking sequence. A design process that includes the effects of manufacturing tolerances and variability in lamina properties will allow for a more reliable and robust structure.

In this Technology Brief, we will demonstrate a methodology that adds reliability and robustness considerations to a traditional stiffness optimization and apply it to the design of a composite aircraft winglet.

Background

An optimal design can be thought of as one that most completely satisfies a set of requirements and constraints. For a lightweight structure, the performance objective is to minimize weight while satisfying allowable stress limits. A more complete optimization process however, should also consider reliability, robustness, manufacturability, and cost.

Software Tools

Isight is a process automation and design optimization solution from SIMULIA. A schematic diagram of the Isight optimization process is shown in Figure 1. The first step is an optimization to find a design that lies on the critical constraint boundary (red outlined dots). Note that the initial design can optionally be determined with a Design of Experiments (DOE) analysis. The reliability of the design is then examined by considering variability in material properties and manufacturing process (red solid dots). Finally the optimal design (large green dot) is determined by ensuring that the design including variability will survive the in-service loads while meeting the reliability criteria.

A number of different simulation programs can be used in a given optimization process. Isight coordinates the execution sequence and exchange of information through the use of components. Isight has over 40 components that allow it to connect with various software products including Abaqus, EXCEL, MATLAB, and CFD codes.

Abaqus was used to perform the structural analyses of the composite winglet. The Abaqus component in Isight was utilized such that the Isight optimization automatically drove the successive Abaqus analyses. The entire process starts by performing a structural optimization before extending it to examine reliability and robustness.

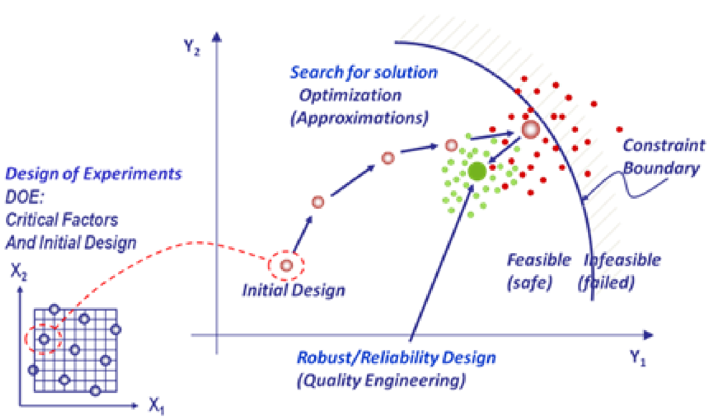

Figure 1: Schematic of the optimization process

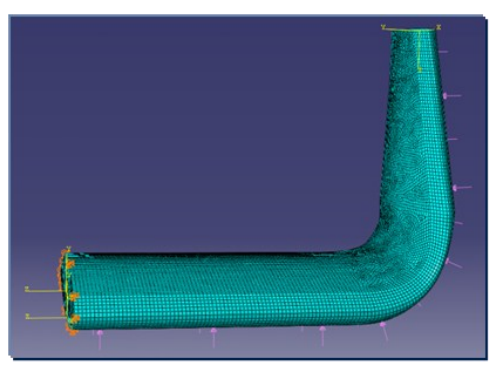

Figure 2: Winglet finite element model in Abaqus/CAE; mesh, boundary conditions, and pressure loads are shown.

Structural Optimization

The structural optimization examined a simplified generic composite winglet. The goal was to minimize weight while keeping the stresses in the composite below the critical level.

The winglet structural analysis model was created in Abaqus/CAE, where the geometry was meshed and the material properties and baseline composite layup were defined. Pressure distribution over the lower and outboard surfaces (Figure 2) is the critical load case.

Isight was used to define the optimization process, variables, objectives and constraints. The Isight interface provides a workspace to drag-and-drop components or activities to define the process, or 'Simflow' (Figure 3).

Our Simflow starts with a Microsoft Excel component that contains the composite material database. The next step in the process is controlled by the Input Arrays component that modifies the composite layup, varying the number of plies and the ply angles. The Data Exchanger component then updates the Abaqus model file. The final step in the process is the Abaqus simulation.

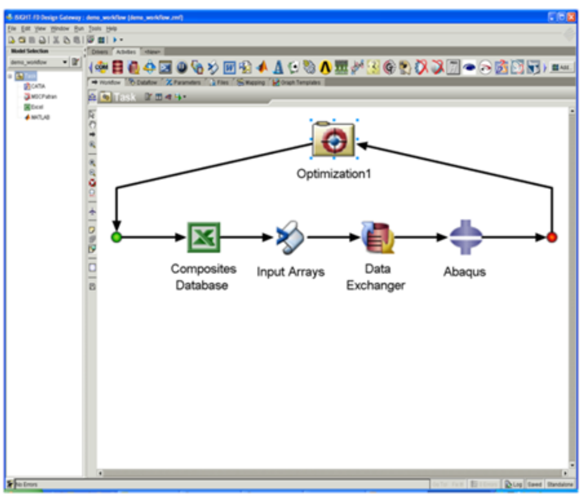

Figure 3: Isight interface with the components used in the winglet optimization

Once the Simflow is created, the optimization parameters are defined. Two objectives are sought: minimize the number of plies, and minimize the Tsai-Wu failure index. By minimizing the number of plies, we also minimize weight and manufacturing cost. During the simulation, each ply layer of each element is evaluated against a constraint that the Tsai-Wu failure index must be below 1.0 (i.e. the ply does not fail).

The design variables are the number of plies, ranging from 2 to 5, and the ply angles, ranging from -90° to 90° with discrete values of [-90°, -45°, -30°, -15°, 0°, 15°, 30°, 45°, 90°]. The NSGA-II genetic algorithm was utilized for the optimization.

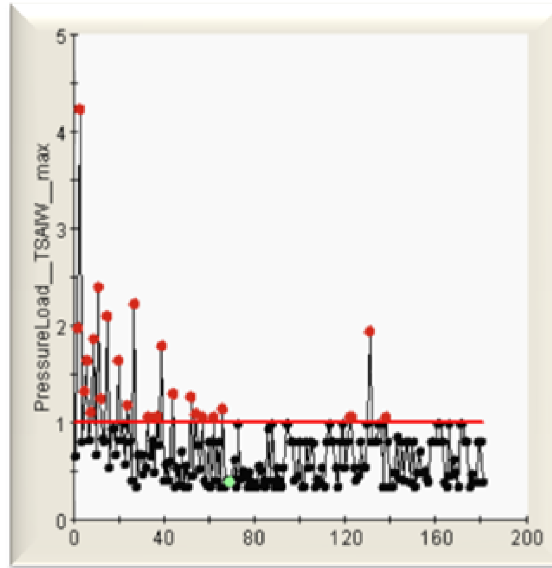

Figure 4: Tsai-Wu failure index value vs. design iteration number

Structural Optimization Results

A large number of possible designs could be created from the variables listed above. Guided by the genetic algorithm, Isight analyzed 181 different alternatives.

Figure 4 displays the Tsai-Wu failure criteria for the various design iterations. Those with failure criteria values below 1.0 are passing (noted with black dots; failing designs are noted with red dots). Figure 5 displays the number of plies for each design iteration. From this view, we can see that no 2-ply designs pass the stress criteria. There are several passing 3- and 4-ply designs and all of the 5-ply designs pass.

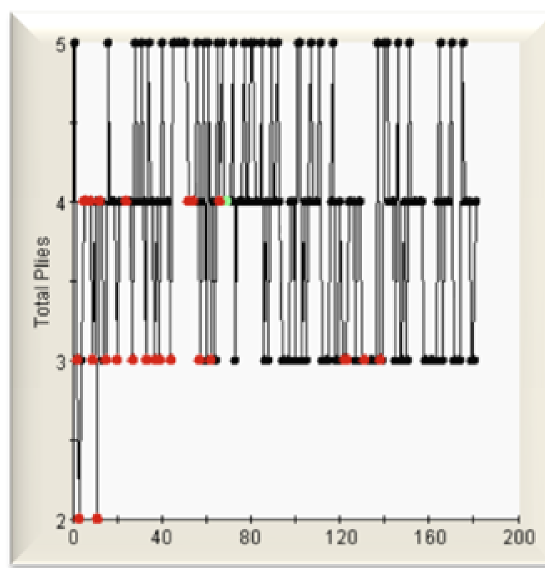

Figure 5: Number of plies in each design iteration vs. design iteration number

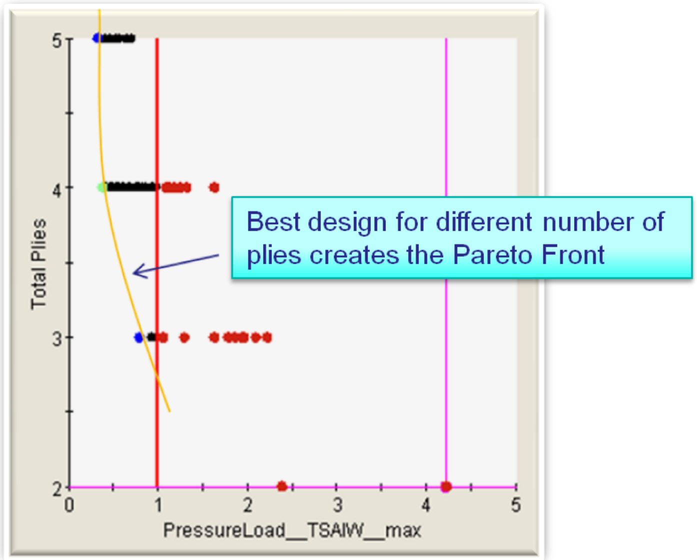

Figure 6: Pareto front for design alternatives

Another way to view the results is to combine Figures 4 and 5 and plot the number of plies against the Tsai-Wu index. The curve passing through the best alternative for a given number of plies defines the Pareto Front (Figure 6).

The final step in viewing and understanding the structural optimization results is to examine the stress analysis results in Abaqus/Viewer. Isight and Abaqus are linked together such that highlighting a design iteration in Isight automatically brings up the analysis results in Abaqus/Viewer for further post processing (Figure 7).

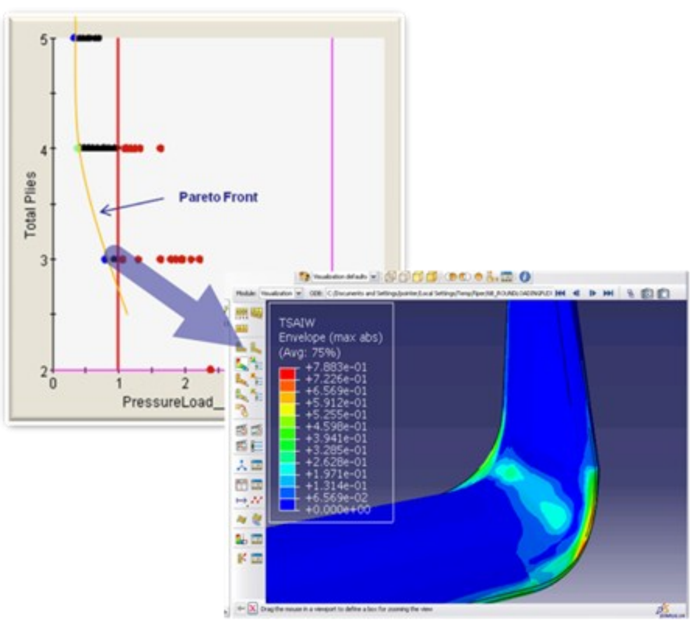

Figure 7: Contour of Tsai-Wu failure index for best 3-ply design

Structural Optimization Conclusion

The conclusion from the structural optimization is that the 3 ply design (blue dot in Figure 6) best satisfies the chosen objective; it is the lightest weight and it passes the Tsai-Wu failure criteria.

Consideration of Reliability and Robustness

We now extend the process to examine the effects of variability in manufacturing and material properties and determine the influence on our structurally optimized design. The questions of reliability and robustness will be answered by performing a Six Sigma analysis in Isight.

Six Sigma Analysis

The Six Sigma component in Isight includes two operating modes. The first performs an analysis to define the quality level of a single design, based on the probability of failure or on the probability of constraint satisfaction (reliability).

The second mode performs a Six Sigma optimization, which performs a Six Sigma analysis at each new design point selected during a robust design optimization strategy. The focus is to reduce variability to ensure that virtually all designs satisfy requirements. The Simflow for the Six Sigma optimization is shown in Figure 8.

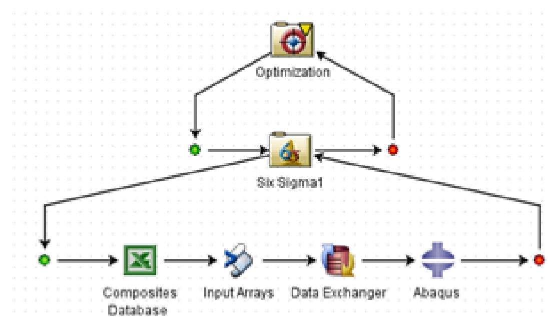

Figure 8: Six sigma optimization Simflow

Six Sigma analyses for both the 3- and 4-ply structurally optimized models were completed using the NSGA-II algorithm. The analyses were carried out to determine the probability of failure given variations in ply angle (+/- 10%), material properties (+/- 10%), and ply thicknesses (+/- 10%). A normal distribution was assumed for each variation.

Additionally, the reliability of the designs was evaluated using the FORM algorithm. FORM is a Most Probable Point (MPP) search method that uses an optimization strategy to find the MPP on each constraint that is closest to the current design, called the Mean Value Point.

Results for 3-ply and 4-ply designs

The structurally optimized 3- and 4-ply designs passed the Tsai-Wu failure criteria and thus had positive margins of safety. But, when we consider variability in the material properties and manufacturing process, the 3-ply design has a 14.3 percent chance of failure and is thus not reliable.

3 ply configuration case based on Tsai Wu criterion – NSGA Reliability results					
Optimized Model	**Run #**	**Number of Runs**	**Probability of failure**	**Reliability technique**	**Cost**
NSGA-II	69	84	14.3%	FORM	Medium

4 ply configuration case based on Tsai Wu criterion – NSGA Reliability results					
Optimized Model	**Run #**	**Number of Runs**	**Probability of success**	**Reliability technique**	**Cost**
NSGA-II	65	65	1 (Sigma = 8)	FORM	Medium

Table 1: Six Sigma results for the 3- and 4-ply designs

As shown in Table 1, the 4-ply design with the same amount of variation in inputs has an 8 Sigma probability of success. This is a reliable design. In practice, an 8 Sigma result could point to an over-designed product; however, the layup must have an integer number of layers, so the 4 -ply design is lightest, most reliable configuration.

Conclusions

In this Technology Brief we have examined the optimization of a composite aircraft winglet and demonstrated that structural optimization that neglects reliability and robustness considerations can lead to unsafe designs.

Isight software from SIMULIA has been developed to enable optimization that accounts for variability in key design parameters, permitting you to more completely explore the design space.

SIMULIA References

- ‘About the Non-Dominated Sorting Genetic Algorithm—NSGA II Technique,’ Isight 5.6 Component Guide, p. 182
- ‘Using the Six Sigma Component,’ Isight 5.6 Component Guide, p. 216
- ‘About the First Order Reliability Method (FORM) and the Second Order Reliability Method (SORM),’ Isight 5.6 Component Guide, p. 221

About SIMULIA

SIMULIA is the Dassault Systèmes brand that delivers a scalable portfolio of Realistic Simulation solutions including the Abaqus product suite for Unified Finite Element Analysis, multiphysics solutions for insight into challenging engineering problems, and lifecycle management solutions for managing simulation data, processes, and intellectual property. By building on established technology, respected quality, and superior customer service, SIMULIA makes realistic simulation an integral business practice that improves product performance, reduces physical prototypes, and drives innovation. Headquartered in Providence, RI, USA, with R&D centers in Providence and in Vélizy, France, SIMULIA provides sales, services, and support through a global network of over 30 regional offices and distributors. For more information, visit www.simulia.com