SIMULATION DRIVEN WEIGHT OPTIMIZATION OF A COMPOSITE UAV SPAR USING MULTISCALE ANALYSIS

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ABSTRACT

Weight reduction to allow for the maximization of useful load is a primary design driver in Unmanned Aircraft Systems (UASs). For this reason, advanced composite materials are prevalent in the UAS Industry. The aim of the recent study was to demonstrate the use of advanced simulation tools to optimize weight of the all composite carry through or center section spar structure of the ARCTURUS T-16XL™ unmanned aerial vehicle through the use of MultiContiuum Technology (MCT) and Response Surface Optimization. MCT is a multi-scale approach for composite materials analysis to predict onset and progression of damage while Response Surface Optimization finds an optimized solution based on variational inputs and responses. Combining them will aid in the redesign and optimization of the current 700 gram composite spar. The authors desire to show a significant reduction in weight of this spar while maintaining design drivers allowing for a substantial increase in payload capacity of the roughly 39 kg (Gross Weight) UAS.

1. INTRODUCTION

Unmanned Aircraft Systems (UAS) are unique tools for both military and civilian markets. While UAS missions continue to expand scope, a major design driver has become the useful load to gross weight ratio. An increase in useful load for a given airframe expands the airframe's envelope in either additional payload, fuel or performance. To this end, composite materials are a major contributor to the design and construction of most major UASs. Flight endurance is no longer a flight crew limitation but time in flight is strongly dependent on fuel consumption since in-flight refueling does not yet exist for UASs. High altitude operations are becoming necessary requiring a reduction in gross weight. The use of advanced composite materials, and the optimization thereof, is critical to maximize flight performance envelopes, endurance and/or mission success.

Over the years, Finite Element (FE) technology has been utilized more with composite component design, and currently most of the commercially available FE codes offer comprehensive and accurate ways of modeling composites. Topology optimization is an FE method that has been widely used for the optimization of metallic structures [1-8] including many aerospace components [9-14] and has now added capabilities for optimizing composite structures [15,16]. With the use of the modern optimization driven design technology available with topology optimization, engineering costs can be drastically reduced while producing designs that are lower weight and higher performance.

Current composite optimization technologies include panel optimization codes that utilize closed-form equations based off of FEA forces and full factorial design scans. There are also composite size FE based optimization methods which use gradient based optimization to size plies of each defined ply angle. Both of these methods can be effective but they require the user to pre-define the thickness zones of the structure. In other words, the optimization routines can only run on a zone that is pre-defined to be of constant thickness. These methods do not allow for the definition of the thickness zones as an output from the optimization run.

2. BACKGROUND

2.1 Composite Optimization Process

The composite optimization process involves 3 steps as follows: 1) Ply Shape Optimization, 2) Ply Shape Sizing, and 3) Ply Order optimization. Ply shape optimization uses a combination of topology and topography optimization methods for composite structures. Once the composite panel geometry is defined, a finite element shell mesh is applied to the geometry, the user selects the ply angles to be considered, defines the loads and boundary conditions on the panel, defines any structural constraints (e.g. buckling), defines any manufacturing constraints for the application, and selects the objective function (e.g. minimize mass). The manufacturing constraints can be a requirement to balance the laminate or ply pairs (e.g. ±45° plies), set a minimum or maximum thickness for any given angle, or set a minimum or maximum thickness of the laminate. The user also selects the number of ply shapes that are desired (e.g. four shapes per ply angle) The ply shape optimization routine then produces a set of ply shapes for each angle per the parameters set by the user.

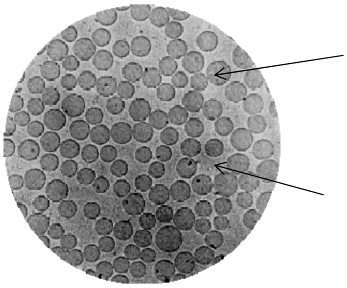
From this step, the ply shape sizing is carried out. The user first determines if the ply shape optimization definitions are acceptable or if modifications are desired. In some cases, the designer may want to modify the ply shapes for manufacturing or other considerations. Once the final ply shapes are determined, the next step is to size the ply shapes. In this step, additional constraints can be applied to the problem (e.g. a strain constraint on the fiber) and the problem is re-run. Again, the objective function must be defined such as to minimize mass. The results of this step give the number of plies to cut for each shape.

The final step is to take the ply information and then apply a ply order optimization methods to define the final lay-up definition of the structure. The ply order optimization method can take into account different requirements such as a limit on the number of adjacent plies with the same angle, a constraint on which angle to have on the outside of the laminate and which angle to have in the core of the laminate. A more complete description of the composite optimization process is outlined in [15,16].

2.2 Multicontinuum Theory Background

The Multicontinuum Theory (MCT) applies continuum mechanics, the representation by average values of quantity, across multiple materials (two in this case) whose physical dimensions are small in comparison to the physical dimensions of the system of interest, yet large enough to capture average behavior. First described by Hill [17], the method evolved from Garnich and Hansen's original proposal [18] to Mayes and Hansen's [19], [20] failure analysis addition and then Nelson, Hansen and Mayes [21] provided improved solutions.

Building on traditional continuum mechanics to determine stress and strain fields for a composite at a point of interest, micromechanics are utilized to establish the needed relationship between the composite and constituents (fiber and matrix). Average constituent stresses and strains are decomposed from the composite results. A schematic of the multicontinuum hypothesis is shown in Figure 1.



$$\underset{\sim}{\sigma}_{\alpha} = \frac{1}{V_{\alpha}} \int_{D_{\alpha}} \underset{\sim}{\sigma}_{\alpha}\left(\mathrm{x}\right) dV_{\alpha}$$

$$\underset{\sim}{\sigma}_{\beta} = \frac{1}{V_{\beta}} \int_{D_{\beta}} \underset{\sim}{\sigma}_{\beta}\left(\mathrm{x}\right) dV_{\beta}$$

Figure 1. The Multicontinuum Concept

Traditional composite analysis methods apply continuum mechanics to a single homogeneous medium. Often dubbed the black aluminum approach, interactions between constituents are neglected. As the presence of two unique materials in a composite distinguish structural response, the MCT approach addresses the constituents and interactions thereof. Having the ability to apply separate and distinct failure theories to the fiber and the matrix allows the MCT approach to address the unique behavior of each constituent. Readily coupled for the finite element method, MCT has been commercialized as the software product Helius:MCT™, an add-on for several finite element analysis software packages.

Within multidirectional laminates, a multi-axial load state exists even under the simplest loading scenarios. Thus, optimizing to first ply failure can be extremely conservative utilizing traditional failure criteria. This is due to failure being based upon lamina level strengths and failure being flagged as soon as the lowest strength value, usually the matrix material, is reached in one lamina. Most likely, this initial failure does not affect stiffness or strength of the structure. The MCT approach provides the ability to understand the behavior of the fiber and matrix as separate but linked materials. This allows for the 1st ply failure to be based upon fiber failure and disregard the 1st ply matrix failure. Basing the optimization of a structure on fiber failure index is still conservative approach as, most likely, a multi-layered laminate will still perform in its intended fashion even after fiber failure occurs in a single ply.

2.3 Multidisciplinary Optimization

When multiple disciplines are involved in analyzing a problem, multi-disciplinary optimization methods are required. In this case, composite optimization is combined with structural analysis that includes multicontinuum theory to predict composite failure. A response surface optimization method was used in this study. The process will be outlined in the following section.

3. RESULTS

3.1 Problem Description

The part to be optimized in this study is the center section or carry through spar of an Arcturus T-16XL UAS. An illustration of the spar is shown in Figure 2. The center section spar is 762 mm in length and is 30.5 mm x 22.5 mm in the cross section. The spar is currently made of 100% unidirectional carbon fiber with the fibers running along the span wise axis of the spar and it is a solid section. Approximate weight of the carry through spar is 700 grams. Topology optimization was run initially which indicated that the spar should be a hollow section as shown in the bottom of Figure 2.

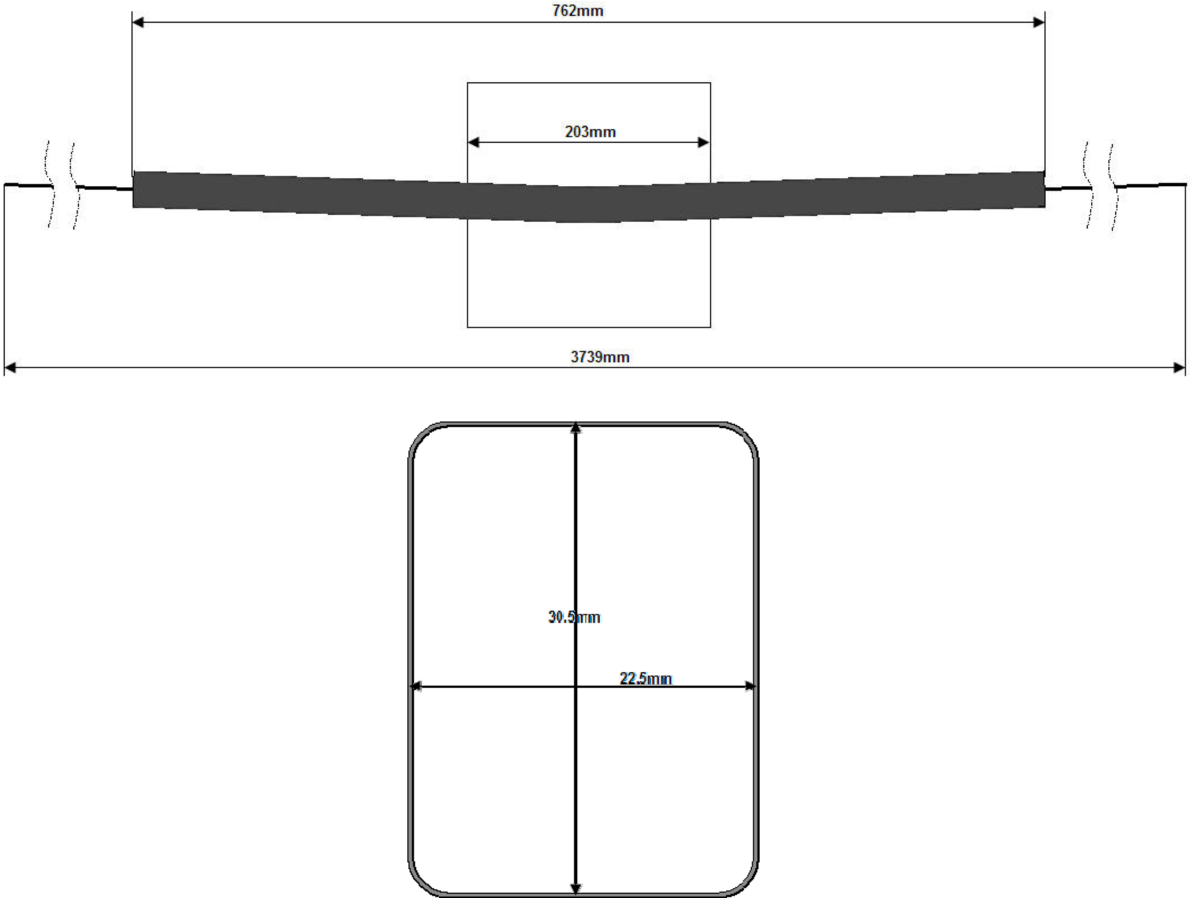


Figure 2. Center Section Spar Geometry

The lift distribution is shown in Figure 3. Total lift force distributed over the wing-span is 4.5 times nominal lift of 378 N. The total vertical force is 2269 N and the total bending moment at the root is 1048 Nm.

3.2 Problem Set-Up

The goal of the study is to evaluate the use of additional fiber angles for the spar in addition to the 0 degrees currently used and to determine if the weight of the spar can be reduced. A hollow section geometry for the spar, as identified from topology optimization, was used for the model. The process used was as follows:

- Use composite optimization methods to determine the ply shapes. The objective is to minimize compliance under the lift distribution shown in Figure 3.
- Carry out multidisciplinary optimization to minimize the total mass while keeping the failure index below 1. The ply shape thicknesses are used as the design variables.

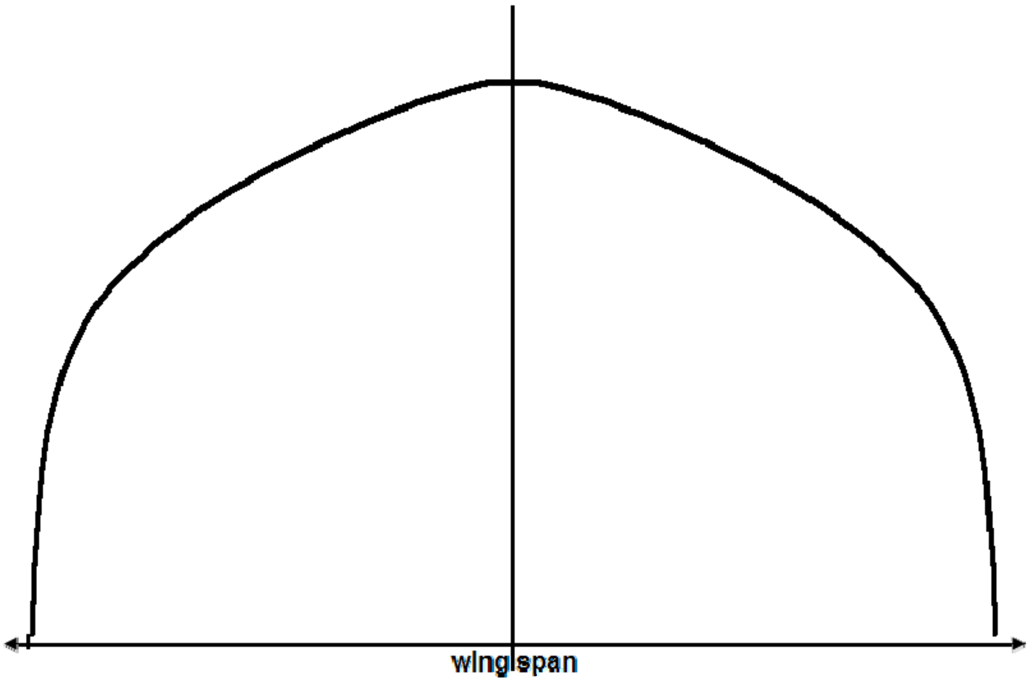
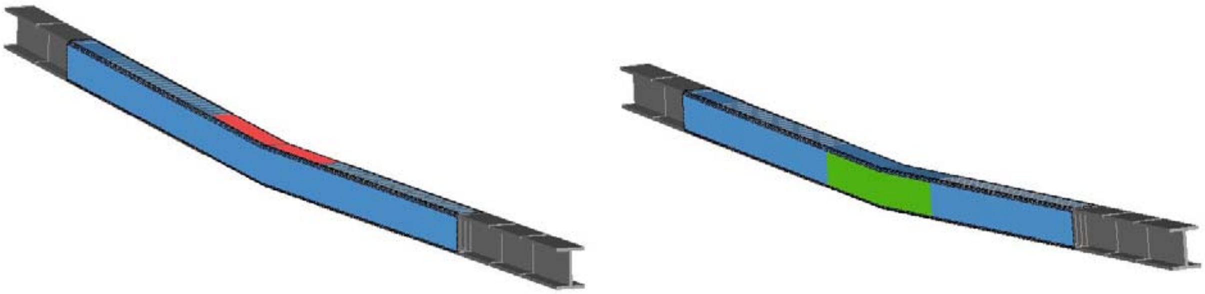


Figure 3. Loading Profile on Spar

The finite element model used for the ply shape optimization consisted of 5085 Elements. The wing spar is modeled as an I-section that gets inserted into the box-spar with the overlap equal to 270mm. The complete finite element model representation is shown in Figure 4 which shows the box beam in blue with the ends of the I-beam shown in gray. The wing spar is connected to the box-spar with load distributing elements at the centroid of each section station. The loading, as shown in Figure 3, is applied to the I-beam. The constraints are applied as shown in Figure 4.

Figure 4 a) shows the constraints in red on the top of the box beam and similar constraints are on the bottom of the beam. In this section, the constraints inhibit movement forward and aft but do not constrain the beam top to bottom to allow for buckling. Figure 4 b) shows the constraints in green applied to the sides of the box beam. Here, the elements are restricted in movement top to bottom but are free to move forward and aft. Total wing span is 3937mm (includes box spar and 2 wing-spars). The ply shape optimization set-up specified 0, 45, -45, and 90 degree plies as the angles to consider for the box beam. A set of 4 ply shapes per angle was also specified. The optimization routine applied a constraint to balance the +45 degree and -45 degree plies.



a) **b)**

Figure 4. Application of Constraints on Box Beam Carry Through Spar

3.3 Optimization Results

The ply shape optimization results are shown in Figure 5. This shows the ply shapes for the box beam from a top view and a side view. Each angle is allowed to have 4 ply shapes and the first ply shape is constrained to be a complete coverage of the beam. Figure 6 shows another view of the ply drop-off pattern along the length of the beam.

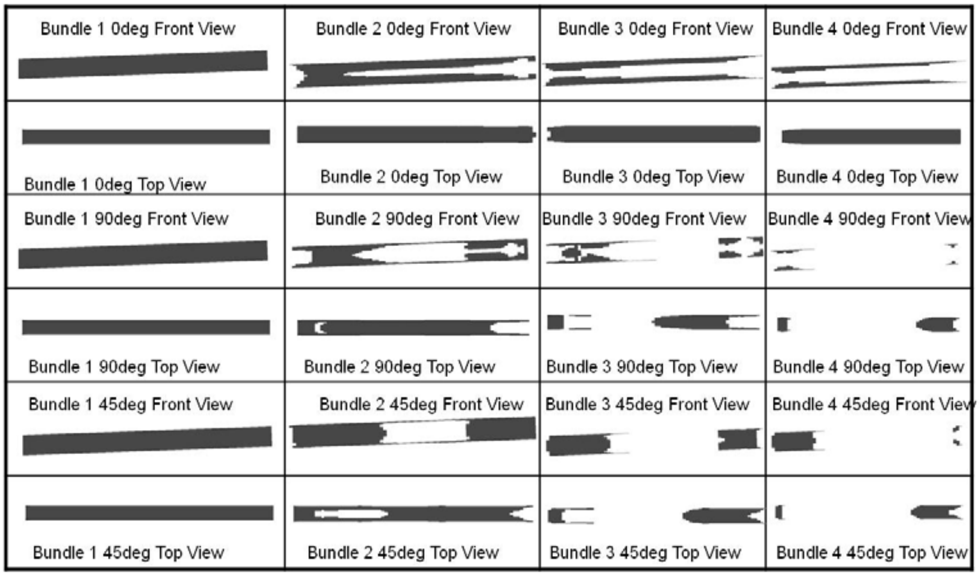
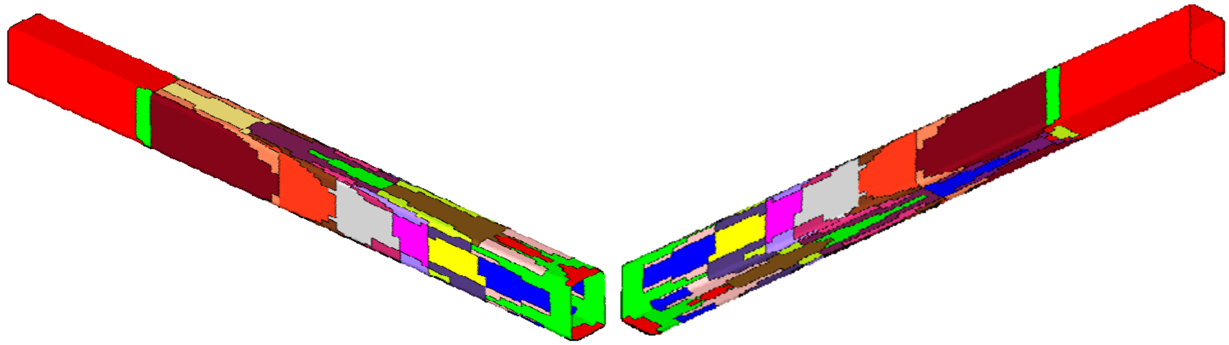


Figure 5. Illustration of Ply Shapes determined by Optimization Method



a) Top Right View b) Bottom Left View

Figure 6. Illustration of Ply Drop-Off Pattern for Box Beam

The next step in the process is to size the ply shapes using the failure criteria from multicontinuum theory as the constraint. The objective function is to minimize the mass of the box beam while insuring that the beam will not fail in any region. The failure criteria is set as the fiber failure as determined by the MCT routine. The process is outlined in Figure 7. The model is submitted to the Study Engine which controls the modification of the design variables for each run. In this case, the design variables are the thickness of each ply shape as shown in Figure 5. Once the study engine determines the ply shape thickness for the run, the XStiff routine is run. Because of an Abaqus/Standard requirement, additional stiffness parameters need to be calculated before each Abaqus/Standard iteration. The analysis is then submitted to Abaqus/Standard utilizing the MCT subroutine (Helius:MCT) to calculate the failure index. The results are then extracted out to the Study Engine which then modifies the design variables and repeats the process. The study engine uses a response surface optimization method to determine the design variables for the iteration. The process repeats until it converges to the lowest weight solution that will not fail.

The final results are shown in Figure 8. The thickness variations, displayed in mm, are shown in the color plots. As shown, the box beams are thicker in the middle of the span and thinner at the ends. The thickness values of all plies are constrained to be a single ply thickness for the first ply bundle. Thickness plots for each individual angle ply considered are shown in Figure 9. The +-45 degree plies were constrained to be balanced so only one plot is shown for the thickness of the 45 degrees plies. A plot of the failure index is shown in Figure 10. The failure index, which is based on fiber failure, is at the upper bound of 1.0 at the center and as a result, the composite beam is thickest at this point. The final weight of the beam is 357 grams which is a 49% weight reduction over the baseline solid section model of 700 grams.

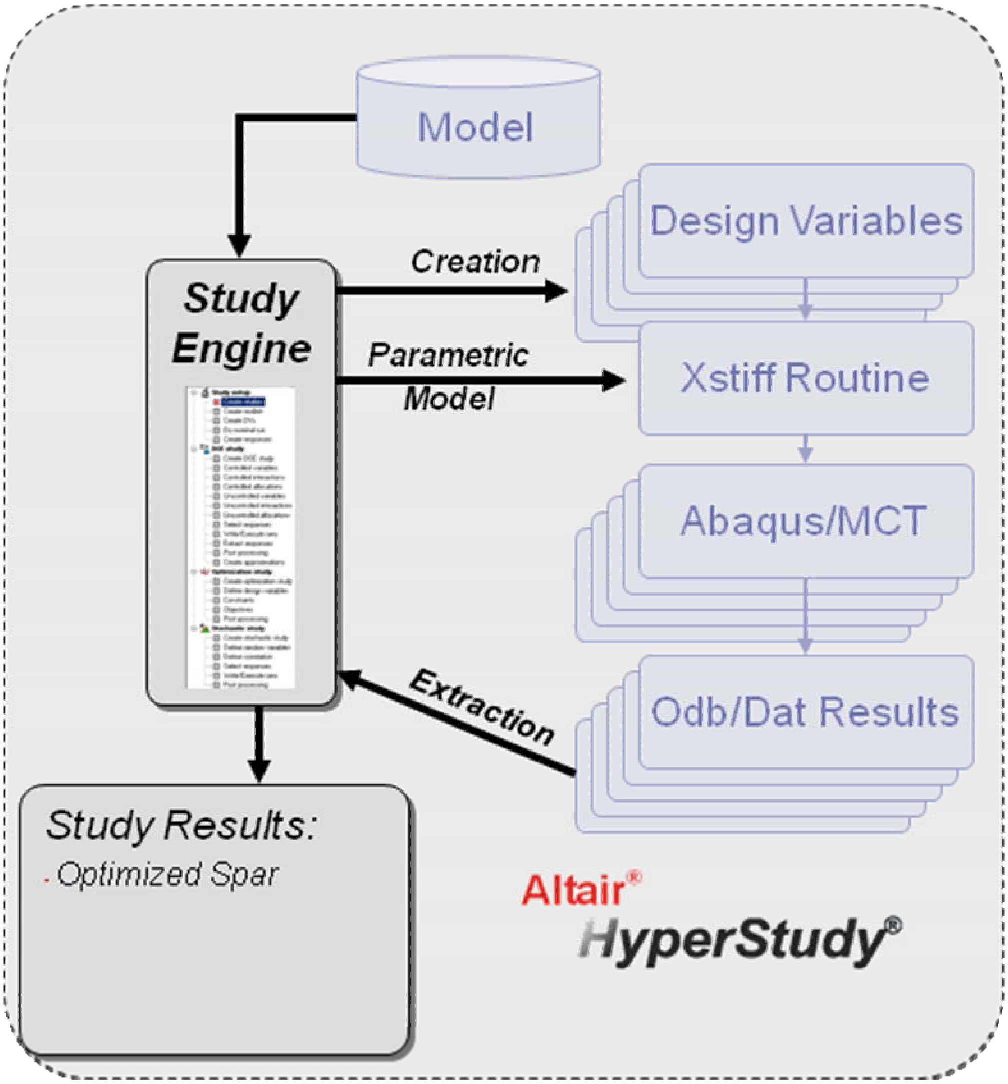


Figure 7. Flow Chart of Optimization Process

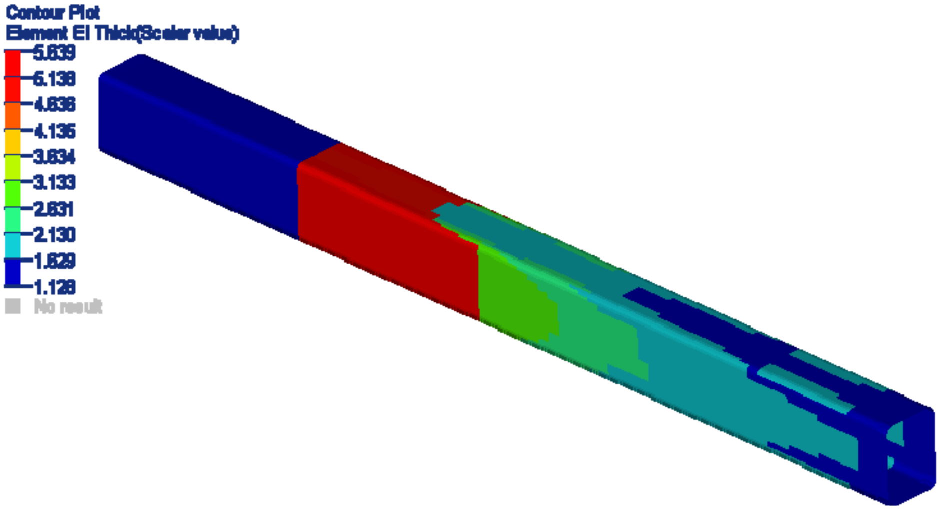
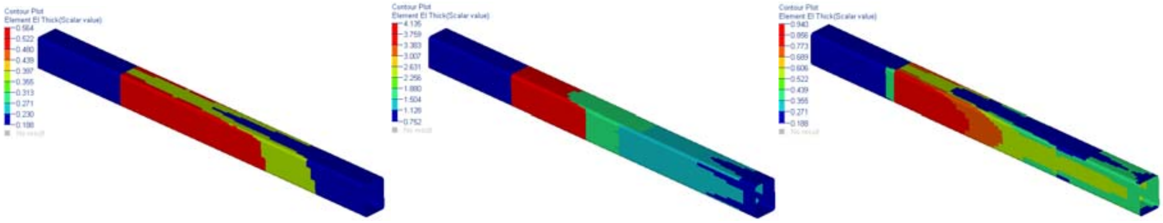


Figure 8. Thickness Plot of Optimized Box Beam Design



a) 0° Plies b) ± 45° Plies c) 90° Plies

Figure 9. Thickness Plots for each Ply Angle

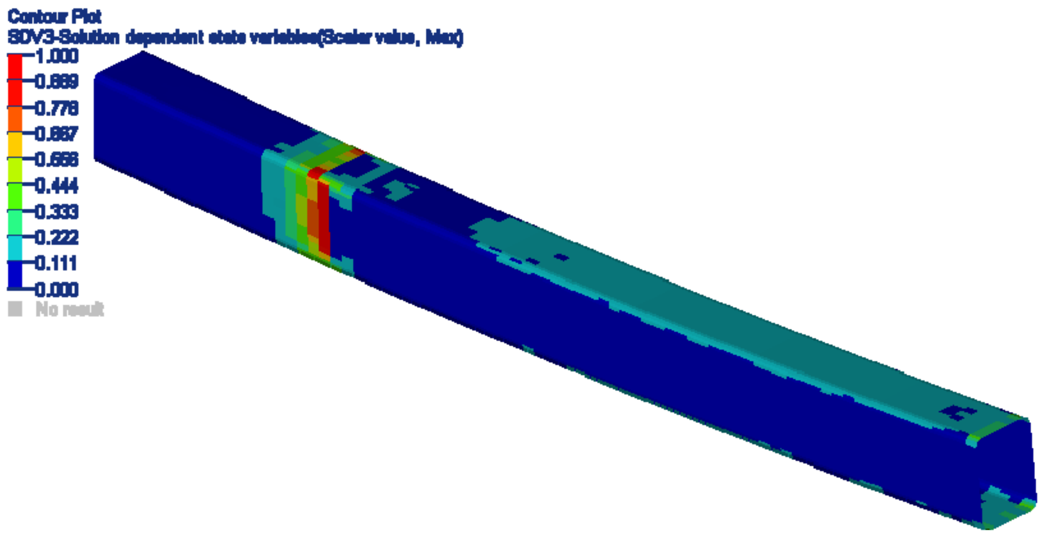


Figure 10. Failure Index Plot of Optimized Box Beam Design

4. CONCLUSIONS

The process outlined in this paper shows that a multi-disciplinary optimization approach to designing composite structures can yield a more weight-efficient design. Composite ply shape optimization combined with response surface optimization and multicontinuum theory will produce a structure with reduced weight while meeting failure constraints at the micromechanical level. The process runs efficiently on modern computer systems and can allow the design engineer to vary many parameters simultaneously to achieve an optimum design. Saving weight on UAV's will mean increased payload, performance, and/or longer range, all very important factors in the success of a UAV platform.

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