MAE 4700 Wing Design Project: Final Report

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Abstract

In this report, we discuss the design optimization of a single 15 meter long aircraft wing made from 2024-T36 Aluminum. We discuss several possible variables and changes we can make to the wing design in an effort to meet several success criteria while minimizing the mass of the final design. We then recommend a design based on our exploration of these variables. Our initial baseline design had a mass of 4840 kg and experienced a displacement of 0.683 m with a factor of safety of 1.29. Our final design has a mass of 8050.4 kg, a displacement of 0.37156 m with a factor of safety of 1.81. We concluded that putting holes into the spars to minimize their role as major structural components was the best approach.

Introduction

Context

Engineers are frequently posed with design problems that require solutions to fit numerous constraints, whether those are dictated by the system that the designs are fitting into, the customer who receives the design, or manufacturability. Computational tools such as ANSYS can be helpful in assisting iterative design processes to provide engineers with optimal parameters to satisfy the aforementioned constraints. These tools; however, are only valuable to use if engineers understand the physical system and are able to properly model its geometry and physical restrictions in simulation software. If this is done properly, design time can be dramatically reduced, leading to greater efficiency and more optimal designs.

This project involves designing and optimizing a 15 meter aircraft wing made from 2024-T36 Aluminum to minimize weight using ANSYS. The simplified geometry model contains the major elements of a modern airplane wing: skin, spars, and ribs. Analysis is conducted assuming the wing is under typical loading conditions in flight, that is, fixed to the fuselage and experiencing loads due to the weight of the structure and aerodynamic pressure. The aerodynamic pressure force is composed of a 2,500 Pa force exerted on the lower wing skin, and a -6,000 Pa force exerted on the upper surface of the wing skin. The negative sign here indicates that the pressure is lower than ambient, so the wing is being pulled upwards.

Constraints

The design variables that can be changed include the thicknesses of the major structural elements, as well as number, locations, and shapes of both spars and ribs. In order to make the design problem well defined, additional constraints such as safety factor (>1.5) and maximum tip deflection (<0.375 m) are imposed.

Mathematical Model and Numerical Solution Strategy

Geometry

We chose to model our wing as a series of midsurface elements. This type of analysis is enabled by the types of geometry we are working with. We are able to approximate the skin, ribs and spars as midsurfaces because they are very thin. Using a mid surface is more efficient than solid elements in the case of very thin surfaces, because a solid element must have a reasonable aspect ratio in order to remain accurate. This means we would need a larger number of solid elements to approximate a thin body.

Mathematical Model

ANSYS creates an underlying mathematical model to create the governing system of equations that provide a basis for the numerical solution strategy. Because the wing is modeled as a thin wall structure, shell theory is used in the mathematical model, which is based on a potential energy minimization. The potential energy approach is used to decrease the effect of errors in generalizing a more traditional equilibrium approach from one to three dimensional problems. In order to find the displacement that provides the minimum potential energy

Potential Energy

In order to determine a final solution, ANSYS uses the theorem of minimum potential energy. This theorem states that the solution to the strong form is a minimizer of the elastic internal energy minus the elastic external energy. Using this, ANSYS can find an expression for the potential energy for each element and add them together, and then take the derivative of this long equation with respect to the unknown degrees of freedom. This allows ANSYS to find an equation for displacement that minimizes the potential energy. The external elastic energy is found using the external force on the body as well as the displacements. The internal elastic energy is found using the derivative of the displacements, the elastic modulus of the material, and the geometry of the element. In order to perform a potential energy minimization, ANSYS uses the external forces and boundary conditions, the material properties, and the geometry, including shell thicknesses, and the undeformed midsurface..

Shell Elements and Degrees of Freedom

For shell elements in ANSYS, the program relies on the assumption that the normal direction remains normal. For the types of elements we are using in this paper, ANSYS assumes there are 6 degrees of freedom per node. This includes three translational degrees of freedom and three rotational degrees of freedom. When calculating the degrees of freedom of the model, ANSYS first assumes all six degrees of freedom are free for all nodes, and then reduces the degrees of freedom based on boundary conditions and known displacements.

Design 1: Default Design

Model Geometry and Mesh

Our initial geometry was the sample provided with the project outline. Specifically, we used the dimensions provided in the Confluence tutorial linked with the project: a wing with two spars 1.25m and 2.5m from the leading edge of the wing, and one rib along the center of the wing (7.5 m from the wing tip).

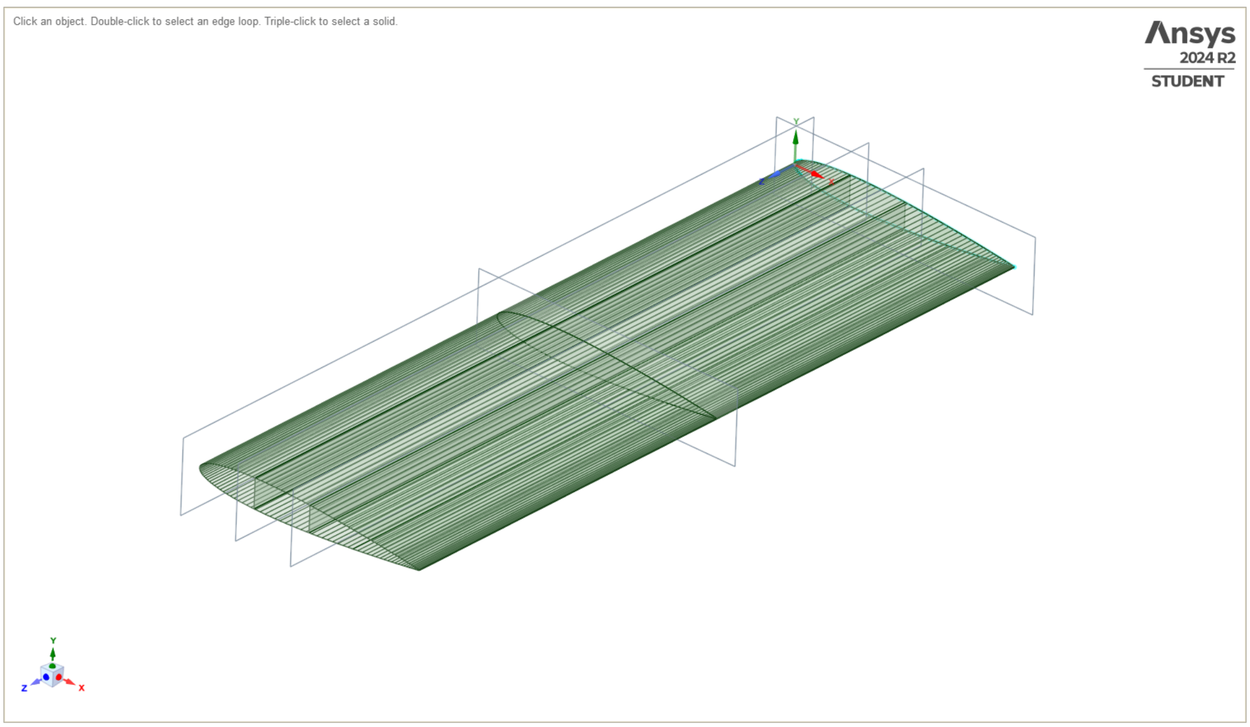


Figure 1: Initial Geometry

The other key dimensions are consistent with the project outline: the wing is 15m in length, and the initial analysis was done with all surfaces being 0.01m in thickness. The meshing was also kept at the default 0.1m value to start. For our following analyses we also used a mesh sizing of 0.1m. This gave us consistency within our design. We included a study on mesh convergence in our results section.

Default Geometry, 0.1m Mesh Size			
Top Skin Thickness	0.01 m	**Mass**	4840 kg
Bottom Skin Thickness	0.01 m	**Tip Deflection**	0.683 m
Rib Thickness	0.01 m	**Max. Effective Stress**	294 MPa
Spar Thickness	0.01 m	**Factor of Safety**	1.29

Table 1: Parameters of Default Geometry

ANSYS Results

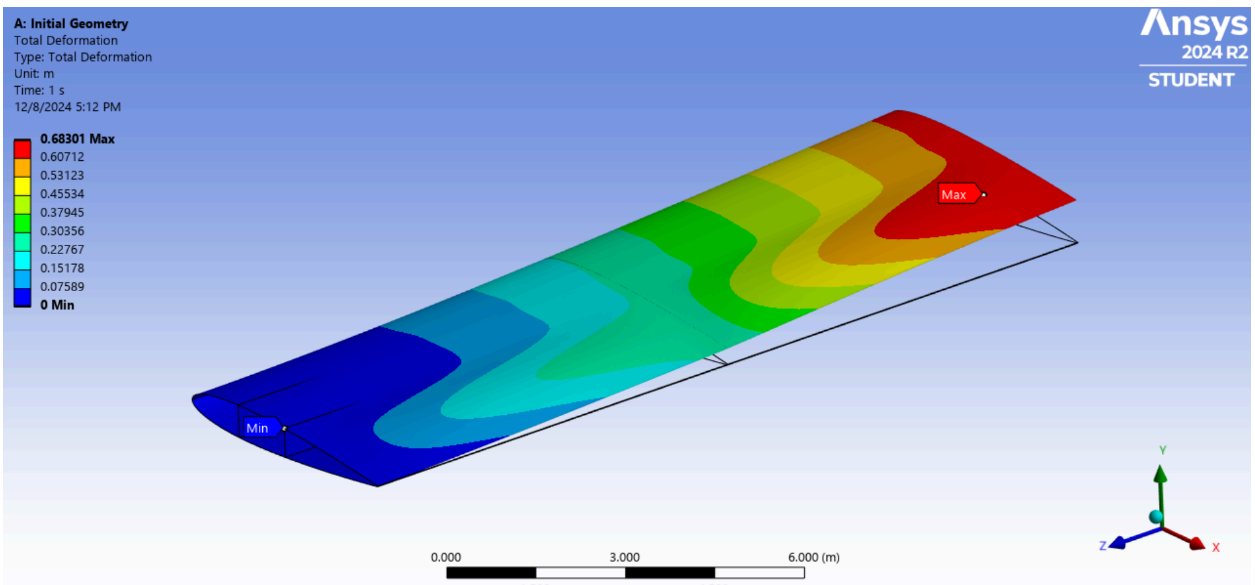


Figure 2: Total Deformation

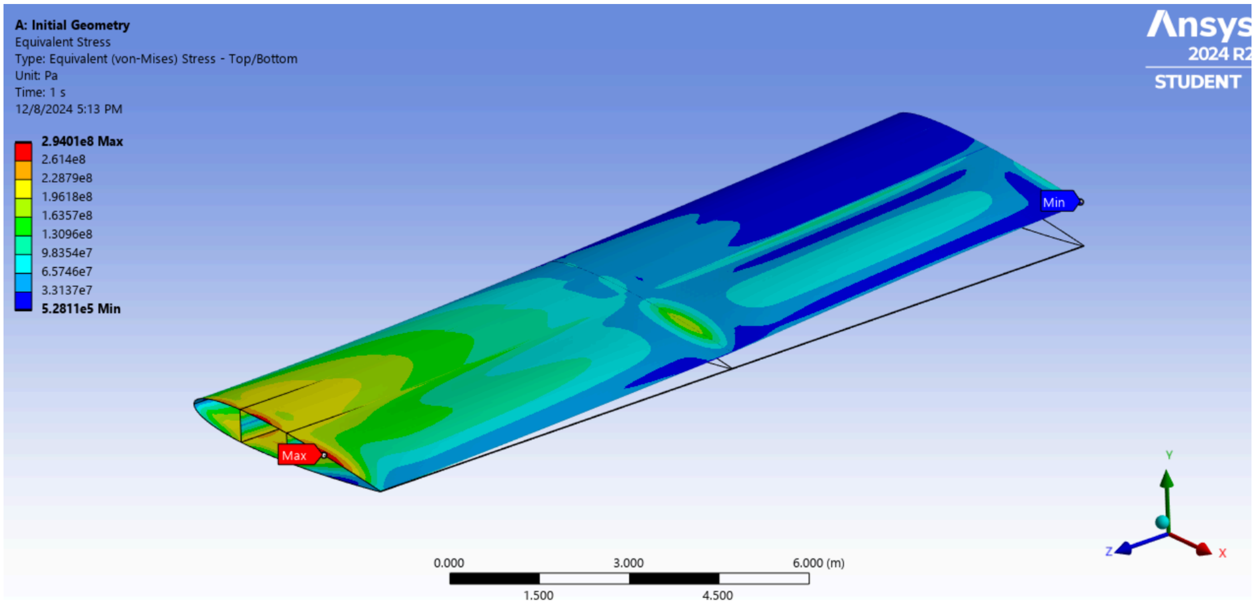


Figure 3: Equivalent Stress

Discussion

The initial design failed to meet the success criteria we defined and therefore must be changed. In future iterations, we will explore how varying skin thicknesses, adding holes in spars, varying the number of ribs and varying the lengths of spars changes our design mass. We will also be using OptiSlang throughout this paper to make sure each result we present is as optimal as possible.

Mesh Sensitivity

In order to determine whether our meshing was producing accurate results, we conducted a mesh convergence study in order to verify our results. We used automatic mesh refinement to dynamically adjust our mesh, our reasoning being that it could provide us more accurate results moving forward. As shown below, this generally increased mesh refinement at surface joints and the fixed end of the wing and along the length of the spars. These locations are extremely thin and have numerous sharp corners, which could lead to levels of stress in an extremely limited surface area.

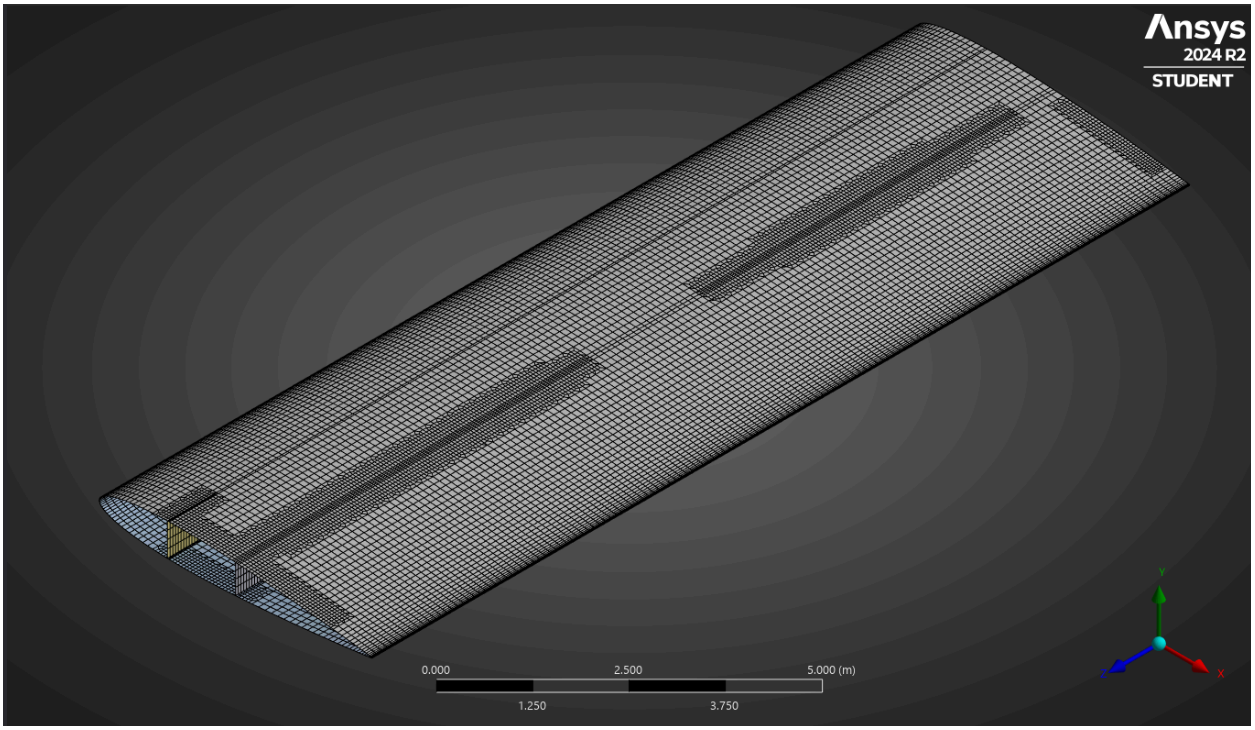
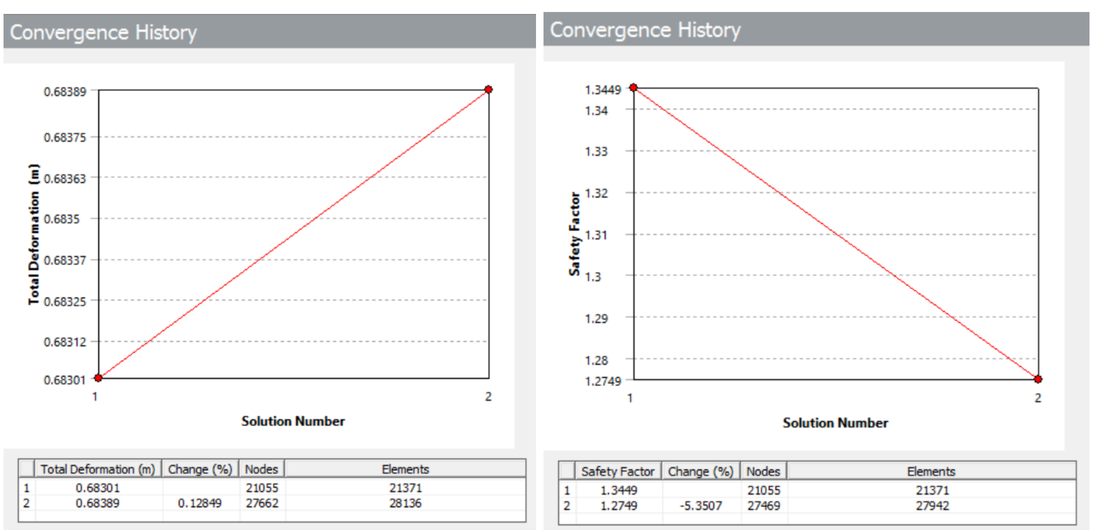


Figure 4: Refined Mesh

Figure 3 (equivalent stress on the default model) shows that we do not have any significant stress concentrations in our initial model. This is most likely because our boundary conditions work well with the design. This means we expect that the adaptive meshing will show convergence of deformation as well as factor of safety. If we had had a stress concentration the factor of safety would not converge, but our convergence results are consistent with our ANSYS stress results.



	Total Deformation (m)	Change (%)	Nodes	Elements
1	0.68301		21055	21371
2	0.68389	0.12849	27662	28136

	Safety Factor	Change (%)	Nodes	Elements
1	1.3449		21055	21371
2	1.2749	-5.3507	27469	27942

Figure 5 and 6: Refined Mesh Convergence of Deformation (left) and Safety Factor (right)

This did cause some changes to the results, though the geometry fails to meet the project criteria with and without the refined mesh; the reported statistics from ANSYS are a mass of 4840.3 kg, tip deflection of 0.6327 m, maximum effective stress of 297 MPa, and a safety factor of 1.275.

Even though this specific geometry in combination with the boundary conditions did not result in stress concentrations, it is important to note the methods of recognizing their occurrences and appropriately adjusting analyses. ANSYS allows users to select a maximum percentage allowable change in solution metrics and if mesh convergence results exceed this limit, there exists a concentration. To adjust analyses, the first step may be to change boundary conditions in the model (e.g. constraining displacements in selected axes instead of using fixed supports). Further steps could include excluding problematic nodes from the solution in post-processing using either select logic or adjusting the geometry to allow for region deselection. It is noteworthy that all of these methods are time consuming, which limits their applicability to this project.

Design 2: Updated Default + Varying Skin Thicknesses

Model Geometry

For reference, running load analysis on the default geometry with the prescribed loading conditions yields a wing mass of 4840.8 kg, maximum tip deflection of 0.67554 m, maximum effective stress of 290 MPa and thus a factor of safety of 1.28. However, our first round of analyses used a bottom-surface pressure of 2000 Pa rather than the 2500 Pa value given with the project outline. This was noticed only after performing optimization - where necessary, it will be clarified what loading conditions were used and what adjustments were made afterwards, if any.

Our analysis continued with running Optislang on the default model with the 2,000 Pa load. The input parameters consisted of the skin thickness (with the top, bottom, and trailing surfaces having equal thickness), individual spar thicknesses, and rib thickness, with the objective being to minimize the wing's mass while keeping the factor of safety at 1.5 or greater and the tip deflection below the 0.375m given in the project statement.

After letting Optislang run, we found the following statistics for the highest-performing design, out of 85 iterations:

Default Geometry, Adaptive Mesh Refinement, 2000 Pa Bottom Surface Pressure, Optislang only			
Skin Thickness	0.016517 m	**Mass**	8991.8 kg
Rib Thickness	0.00345 m	**Tip Deflection**	0.322 m
Spar Thickness	0.041017 m	**Max. Effective Stress**	134.5 MPa
Wing Tip Thickness	0.01 m	**Factor of Safety**	2.81

Table 2: Parameters of Default Geometry After Optislang, 2000 Pa

After later noticing our mistaken pressure condition, we tested the same, unchanged geometry with the given 2500 Pa condition:

Default Geometry, Adaptive Mesh Refinement, 2500 Pa Bottom Surface Pressure, Optislang only			
Skin Thickness	0.016517 m	**Mass**	8991.8 kg
Rib Thickness	0.00345 m	**Tip Deflection**	0.347 m
Spar Thickness	0.041017 m	**Max. Effective Stress**	144.2 MPa
Wing Tip Thickness	0.01 m	**Factor of Safety**	2.62

Table 3: Parameters of Default Geometry After Optislang, 2500 Pa

Evidently, while the misapplication of the load condition isn't ideal for optimization, of course, the difference is small enough to not have affected these results - this geometry still meets the requirements.

Discussion

Further analysis was done using manual optimization, but using unique thickness values for each section of the skin: the top, bottom, and trailing surfaces. This was done as an exploratory analysis, since on a real airplane wing, these surfaces should be able to be made independently of each other and thus have different thickness values. Additionally, given the asymmetric nature of the loading, we expected there to be a benefit to doing so. Since the wing deforms upwards, it should be more efficient to reinforce the top surface than the bottom surface, since the top surface is curved in the upwards direction, which should help resist the deflection - like a pizza slice.

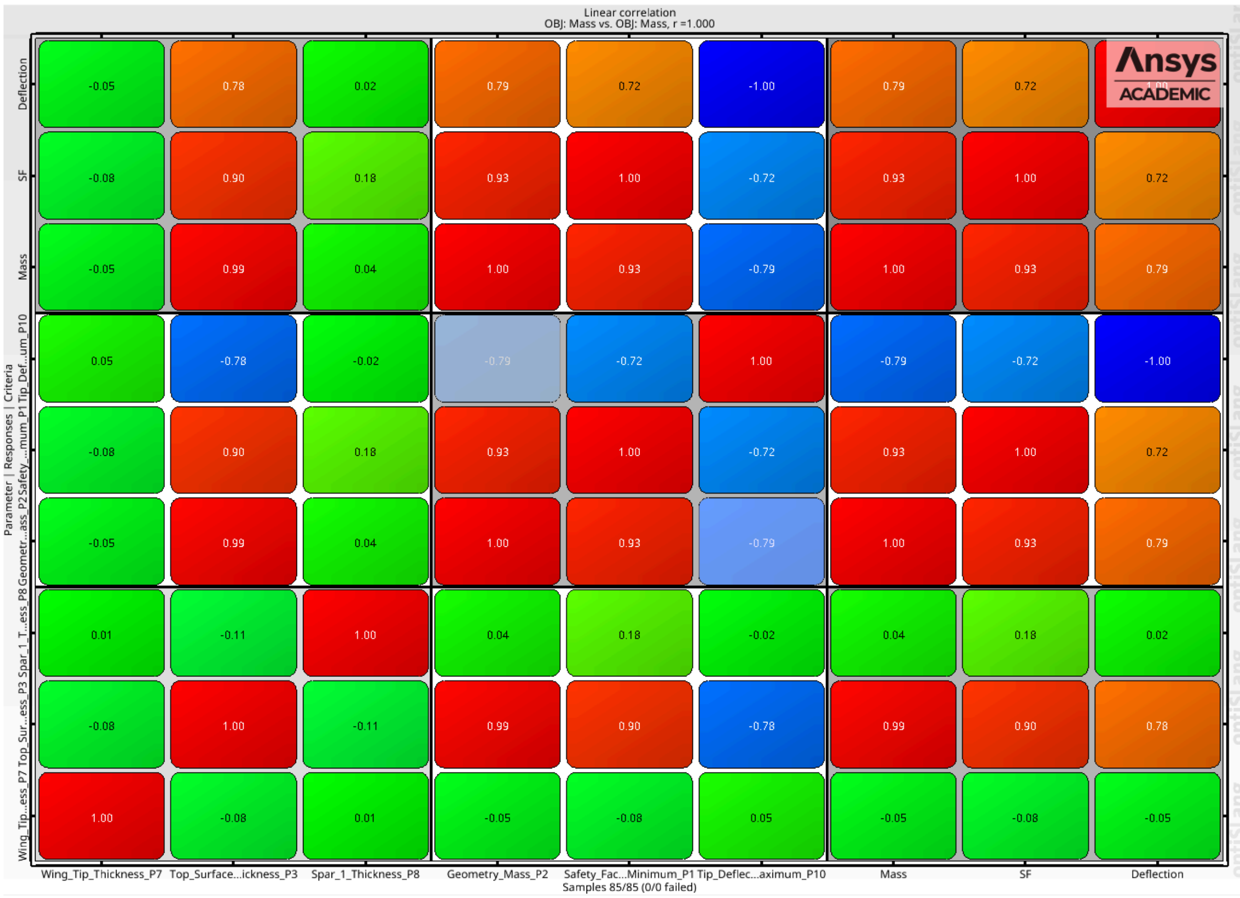


Figure 7: Correlation Matrix For Updated Default Geometry

We based our manual optimization off of the above correlation matrix produced from the 85 Optislang sample designs. Looking at our major criteria, we saw that the tip deflection was much closer to its limit than the effective stress. Thus, an ideal parameter to change would've been one that lowered mass while maintaining or lowering tip deflection and maintaining or increasing maximum stress - however, no such parameter exists. This makes physical sense, as it doesn't stand to reason that making any surface thinner wouldn't worsen tip deflection, but it left us with only one significant way forward with this geometry: to individually alter skin thicknesses prioritizing the top surface over the bottom one for more efficient use of mass. While not expressly allowed in the project outline, we saw it as a worthwhile option to explore.

Surprisingly, however, our results seem to disagree with this idea, at least on appreciable scales. Consider the following data points taken from consecutive manually-tested design points where all unlisted parameters were kept constant after running the Optislang optimization:

Varying Skin Geometry, 2000 Pa Manual Optimization after Optislang				
Top	**Bottom**	**Mass**	**Tip Deflection**	**Max. Stress**
0.0155 m	0.0135 m	8122.5 kg	0.37031 m	158 MPa
0.0145 m	0.0145 m	8122.5 kg	0.36954 m	155 MPa
0.0135 m	0.0155 m	8122.5 kg	0.37088 m	163 MPa

Table 5: Comparing Varying Skin Geometries (2000 Pa Results)

Note that the highest performing design is the one with the top and bottom surfaces being equal in thickness. Reinforcing the top relative to the bottom is very slightly better than reinforcing the bottom relative to the top, which aligns with our initial thinking, but it's surprising to see that even changes as small as +/- 0.001 m are seemingly large enough to overshoot the range over which we'd see the expected structural benefits of favoring the top surface. Considering, though, that the tip deflection is only allowed to be 2.5% of the wing's length and the top and bottom wing surfaces aren't curved particularly strongly, this does make physical sense.

Our final result after Optislang ran on the default geometry and manually optimizing the geometry for multiple skin thicknesses is as follows:

Varying Skin Thicknesses Geometry, 2500 Pa Bottom Surface Pressure, Optislang and Manual			
Top Thickness	0.01525 m	**Mass**	8490.1 kg
Bottom Thickness	0.01525 m	**Tip Deflection**	0.37489 m
Trailing Thickness	0.01525 m	**Max. Effective Stress**	157 MPa
Rib Thickness	0.00345 m	**Factor of Safety**	2.41
Spar Thickness	0.041017 m		
Wing Tip Thickness	0.01 m		

Table 6: Varying Skin Thickness Final Result

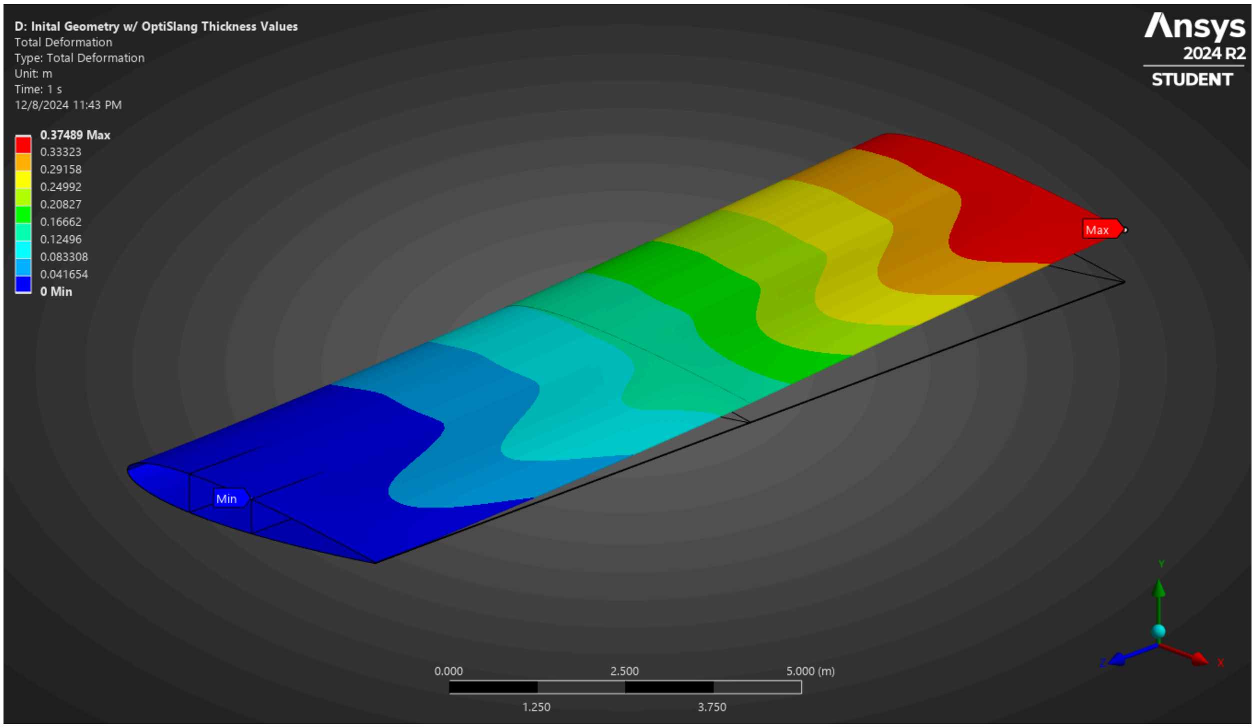


Figure 8: Tip Deflection for Updated Default Geometry

Design 3: Holes in Spars

Model Geometry

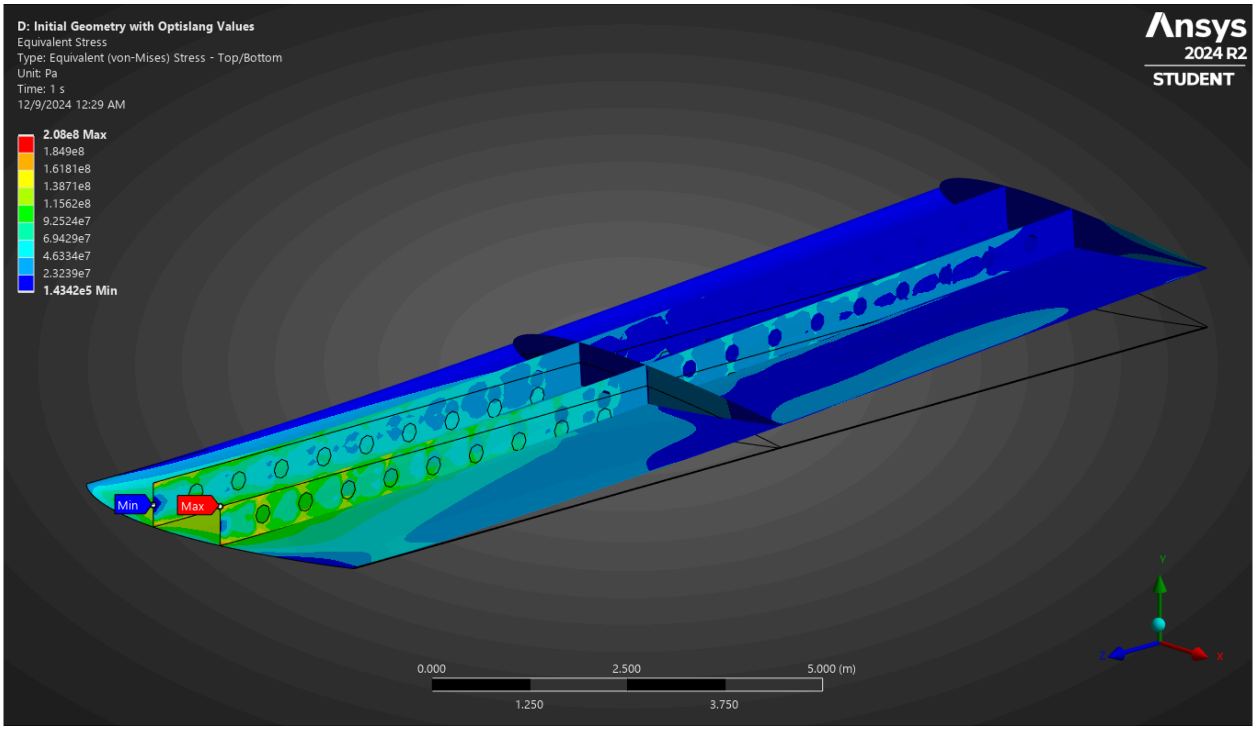


Figure 9: Interior Geometry of Wing

The above figure is an interior view of the default wing geometry with equivalent stress mapped and deflection visible. Our thinking with our third design was that, absent of being able to modify the essential shape of the spars, putting holes through them in the y-z plane might improve their ability to resist bending per unit mass, similar to the thinking behind the design of I-beams: by removing mass from the midplane and concentrating it at the top and bottom of the member, it can better resist upwards deflection relative to its mass by way of having a higher moment of inertia in that direction. While the spars are a somewhat small part of the design, our correlation matrix produced using Design 1 shows that their mass can contribute to decreasing the skin thickness and raising the factor of safety. Since the correlation between spar thickness and skin thickness is greater than that between spar thickness and mass, we decided it'd be worthwhile to toy with the spars to eke out better performance from our design.

Our geometry simply consisted of putting 18 circular holes along the centerlines of each spar, spaced 0.75 m apart from one another and the edges of the spars. Each hole is 0.25m in diameter.

ANSYS Results

Note that this model was tested with 2500 Pa loading from initialization.

For our manual optimization, we started with the Design 1 Optislang results for the 2500 Pa model and manually iterated from there. Our results are as follows:

Spars With Holes, 2500 Pa Bottom Surface Pressure, Manual Optimization Based On Design 1			
Skin Thickness	0.014 m	**Mass**	8803.8 kg
Rib Thickness	0.00345 m	**Tip Deflection**	0.37359
Spar Thickness	0.066 m	**Max. Effective Stress**	245 MPa
Wing Tip Thickness	0.01 m	**Factor of Safety**	1.54

Table 7: Parameters of Spars-With-Holes Geometry After Manual Optimization

After manual optimization, we ran Optislang with the same design constraints and objectives as usual. This is our best result after 85 design variations:

Spars With Holes, 2500 Pa Bottom Surface Pressure, Manual Optimization + Optislang			
Skin Thickness	0.017801 m	**Mass**	8050.4 kg
Rib Thickness	0.0036804 m	**Tip Deflection**	0.37156
Spar Thickness	0.01 m	**Max. Effective Stress**	208 MPa
Wing Tip Thickness	0.0056042 m	**Factor of Safety**	1.81

Table 8: Parameters of Spars-With-Holes Geometry After Manual Optimization and Optislang

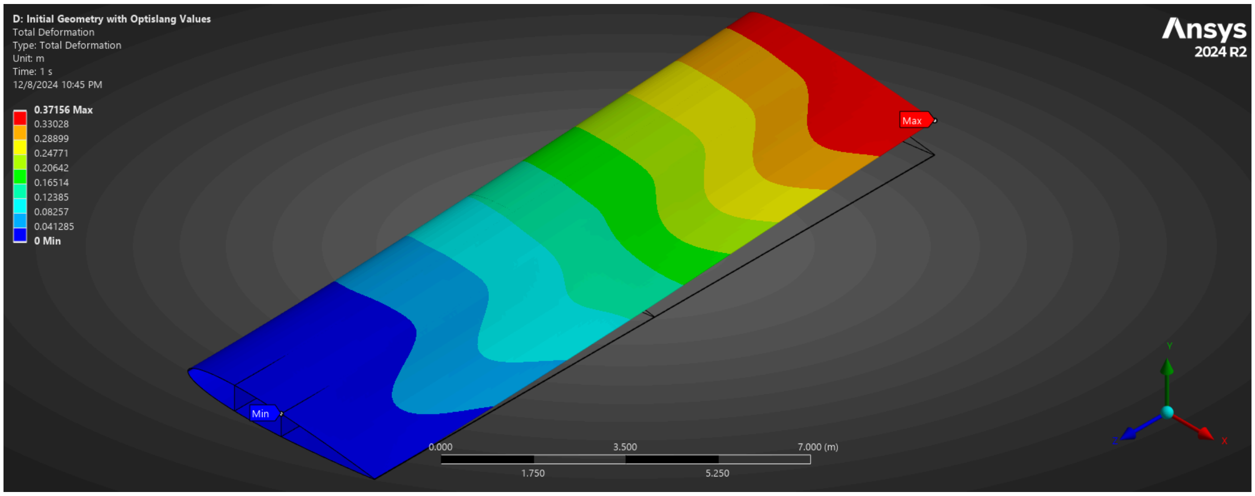


Figure 10: Design 3 Total Deformation

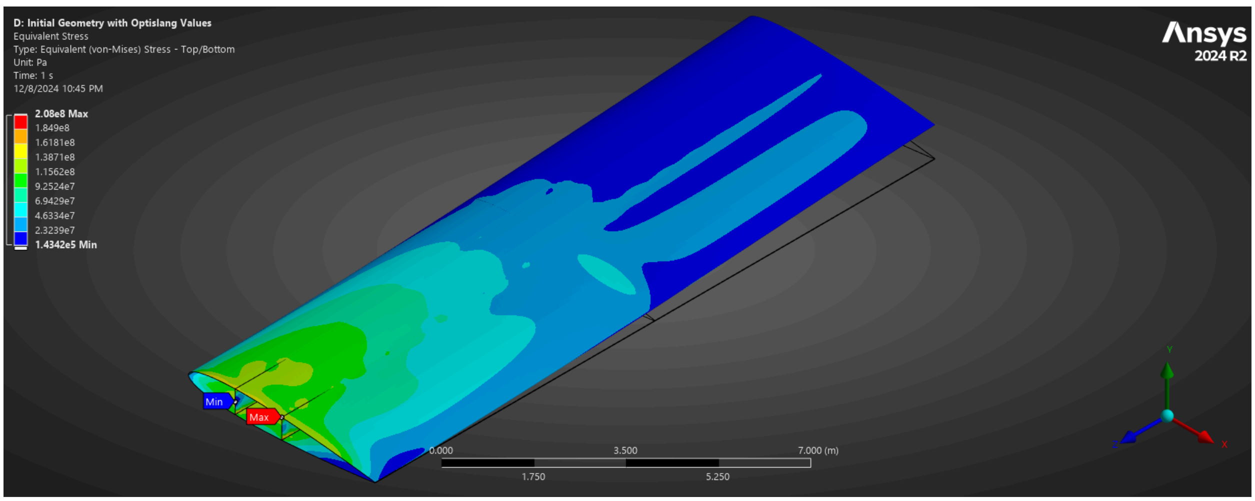


Figure 11: Design 3 Effective Stress

Discussion

It’s incredibly interesting to see that Optislang actually found that de-emphasizing the spars would improve our performance. The correlation matrix might point us towards an explanation:

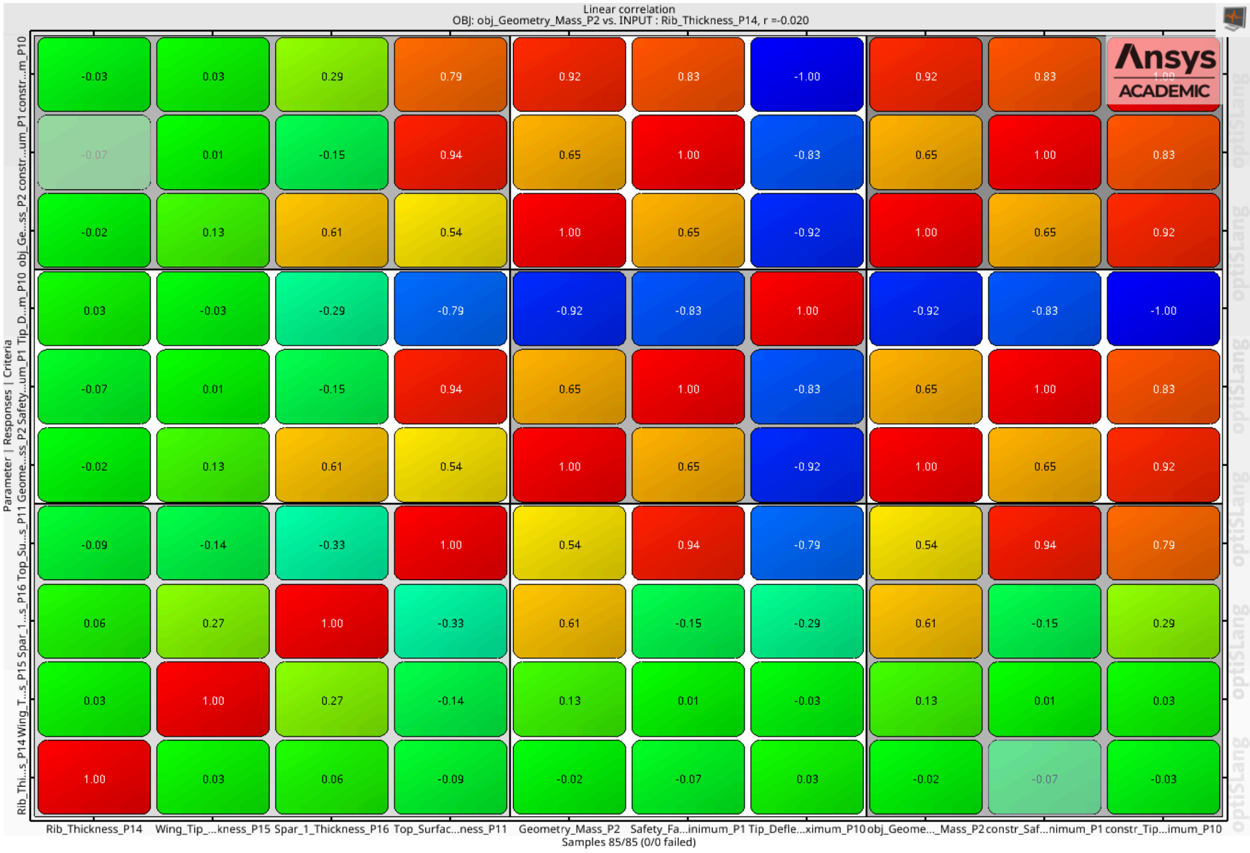


Figure 12: Design 3 Correlation Matrix

Raising the spar thickness is associated with raising the mass, *decreasing* the safety factor, and decreasing the tip deflection, while raising the skin thickness raises mass, increases safety factor, and decreases tip deflection simultaneously. Additionally, past Optislang results - while not exhaustive - put much more emphasis on the spar thickness when the spars didn't have holes and thus should have been less structurally efficient by mass. It could be the case that adding holes changed the best use case of the spars: solid spars ought to be thick to be used as major load-bearing components, but spars with holes might be better of being thin, their low mass making them better suited to resisting buckling of the top and bottom surfaces while the skin takes on the bulk of the load. It's yet another case where our results don't match our expectations, but we're still left with a strong contender for our final design.

Design 4: Changing Number of Ribs

Model Geometry

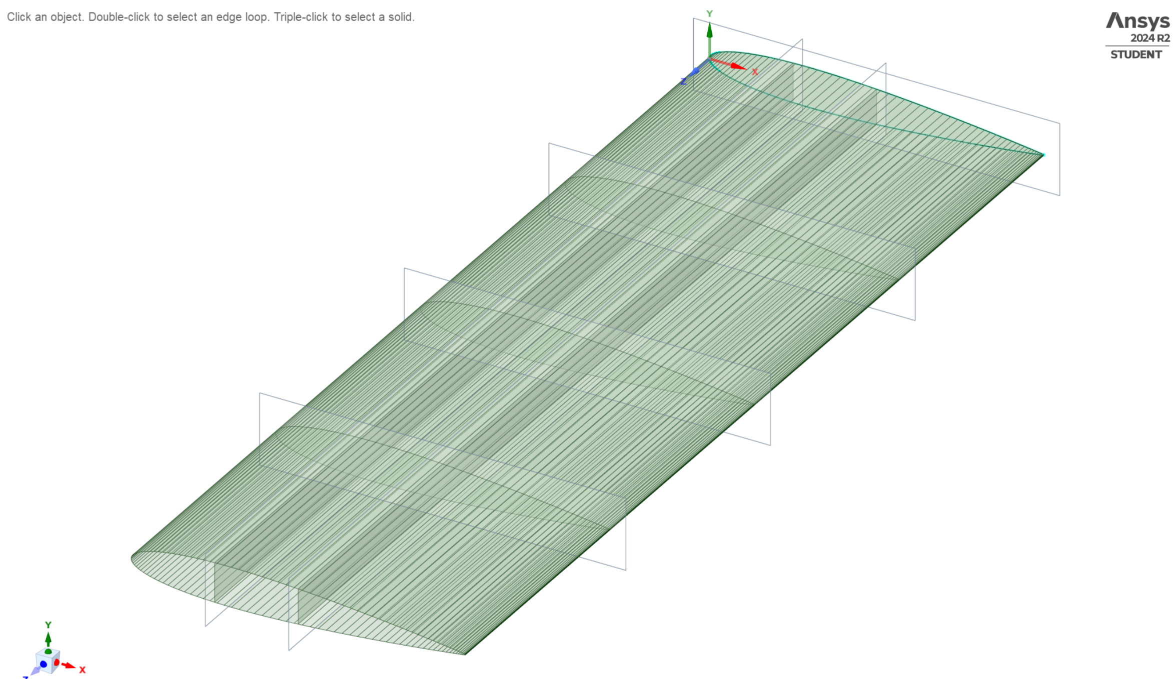


Figure 13: Spaceclaim Model Geometry with Four Ribs

For this model, we started with the default base geometry, but then increased the number of ribs to three. This allowed us to isolate the impact of increasing the number of ribs from the number in the default model. We then ran OptiSlang to determine the optimal thicknesses for all of the surfaces. For simplicity, it was assumed that the ribs all had the same thicknesses. The parameters for the lightest design which passed all of our success criteria are shown here:

Four Rib Geometry, 0.1m Mesh Size, Optislang Optimized			
Top Skin Thickness	0.0165 m	**Mass**	9031.32 kg
Bottom Skin Thickness	0.0165 m	**Tip Deflection**	0.346 m
Rib Thickness	0.00345 m	**Max. Effective Stress**	146 MPa
Spar Thickness	0.04102 m	**Factor of Safety**	2.58

Table 9: Parameters of Lightest Four-Rib Geometry

ANSYS Results

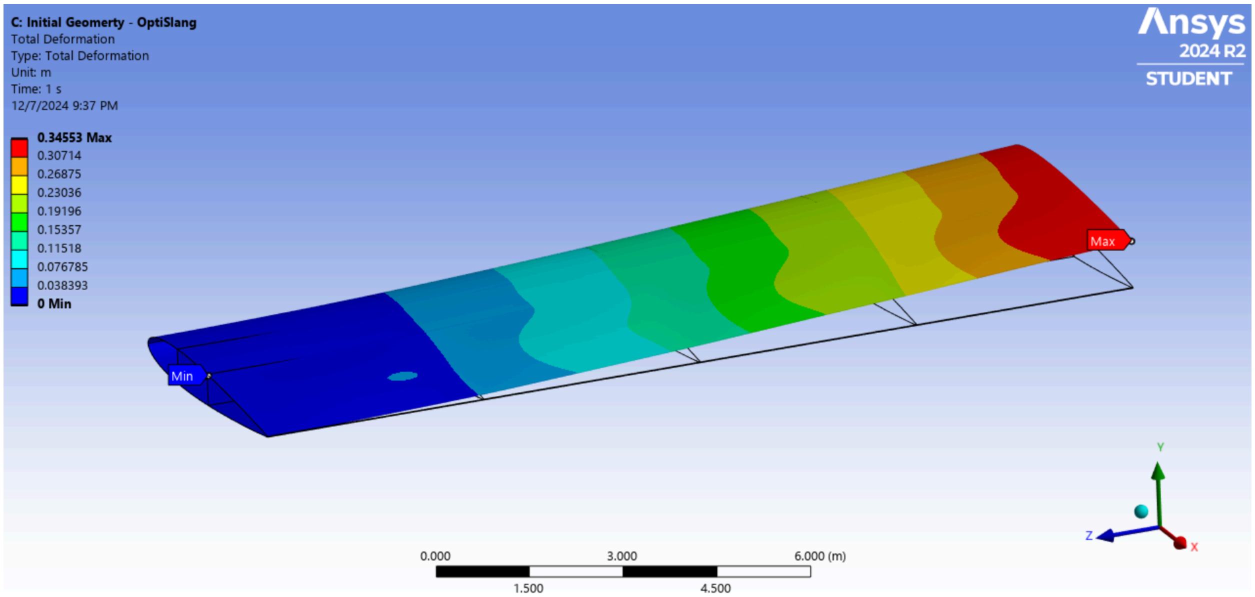


Figure 14: Total Deformation

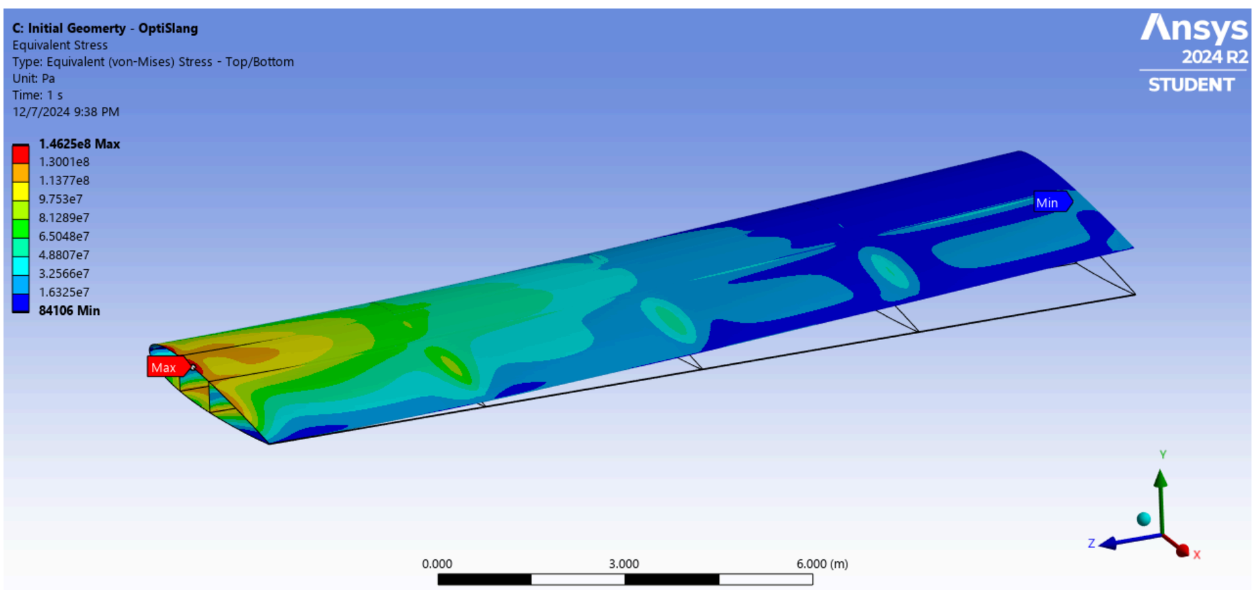


Figure 15: Equivalent Stress

Discussion

This design iteration has shown that increasing the number of ribs does not change the tip deflection significantly, and only ends up increasing the mass of the final design. By increasing the number of ribs, you increase the number of locations where load is transferred to the spars in practice, which should lower the total bending moment on the spar, but in our model increasing the number ribs does not affect the load of the spar significantly, because the load is transferred to the spar by the skin itself. As a result of this analysis, it has been concluded that we should stick with the original number of ribs, or even decrease down to one rib.

Design 5: Changing Length of Spars

Model Geometry

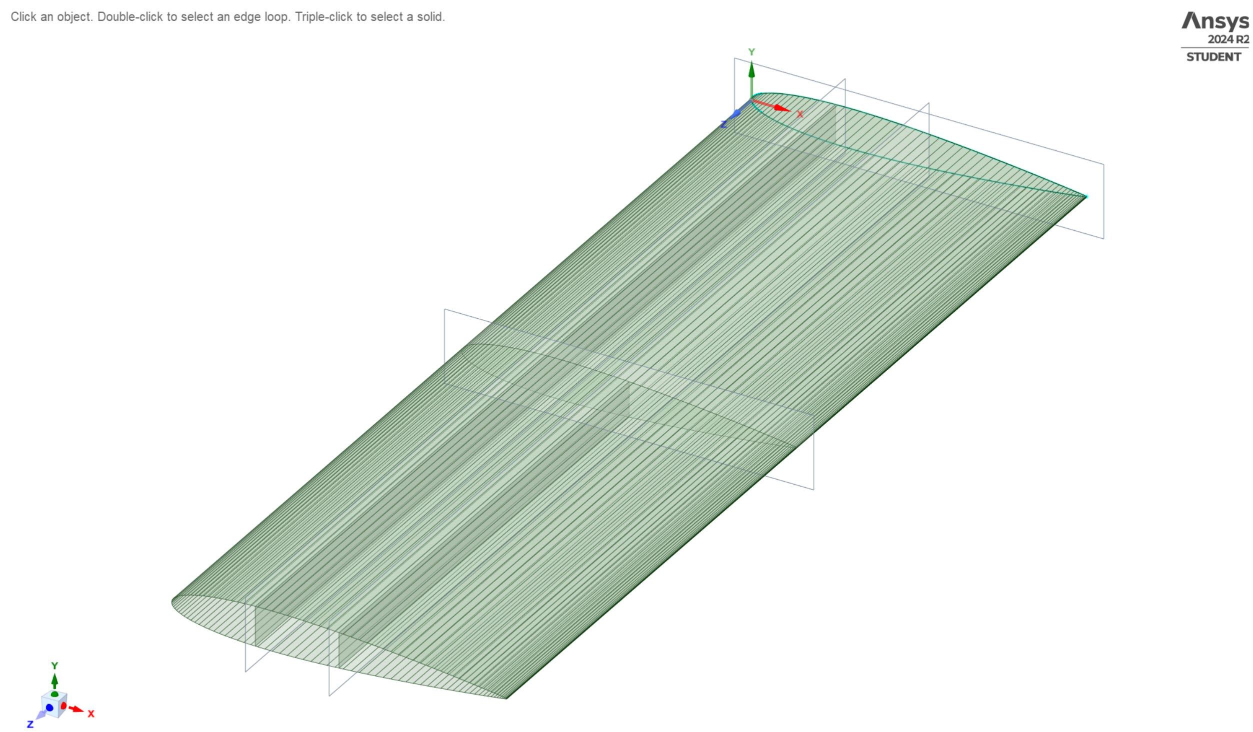


Figure 16: Spaceclaim Model Geometry with Shorter Aft Spar

For this model, we decreased the length of the aft spar to about 7.5 meters long. We theorized that this would be an effective way to reduce weight since the highest stresses are located at the base of the wing. We then ran OptiSlang to determine the optimal thicknesses for all of the surfaces. The parameters for the lightest design which passed all of our success criteria are shown here:

Shorter Aft Spar Geometry, 0.1m Mesh Size, Optislang Optimized			
Top Skin Thickness	0.0165 m	**Mass**	8478.5 kg
Bottom Skin Thickness	0.0165 m	**Tip Deflection**	0.3712 m
Rib Thickness	0.001 m	**Max. Effective Stress**	181 MPa
Spar Thickness	0.04 m	**Factor of Safety**	2.08

Table 10: Parameters of Lightest Short Aft Spar Geometry

ANSYS Results

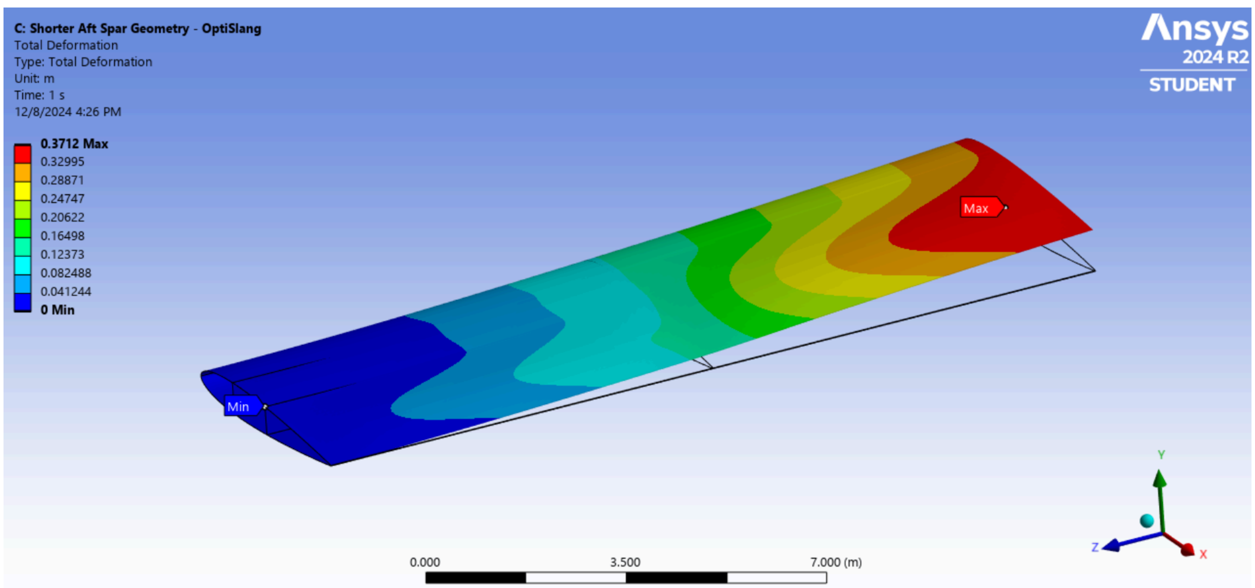


Figure 17: Total Deformation

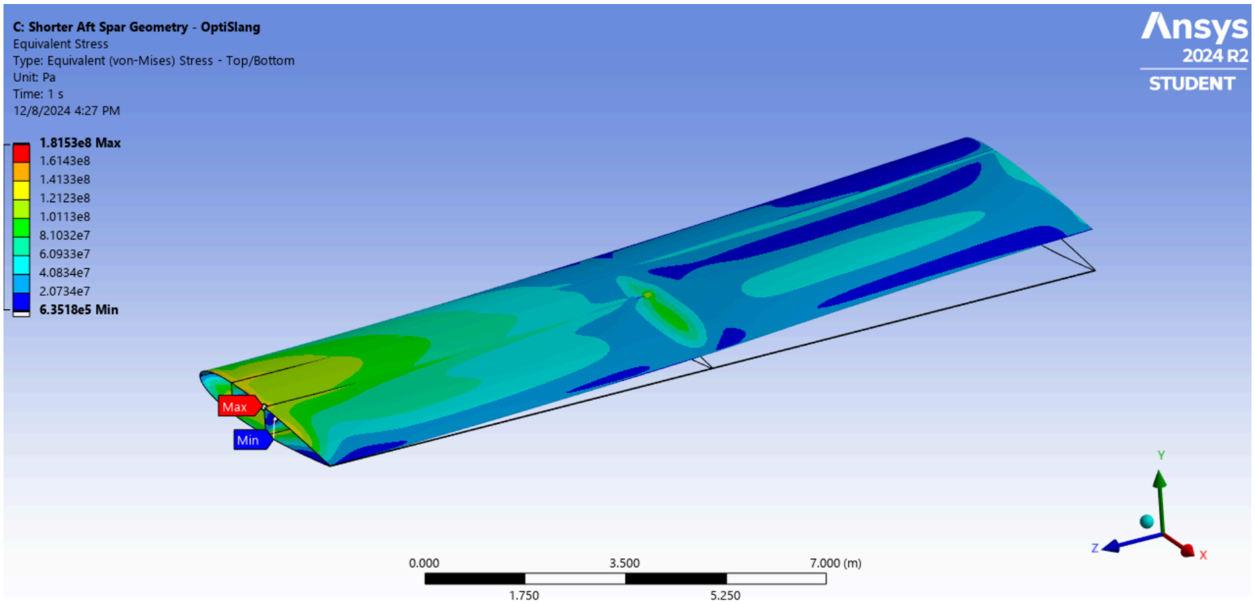


Figure 18: Equivalent Stress

Discussion

This design iteration has produced a wing with very low weight that still meets our design success criteria. It is recommended that the final design includes some version of shortened spars as this is an effective way to reduce weight while meeting success criteria.

Design 6: Holes in Spars and Ribs

Model Geometry

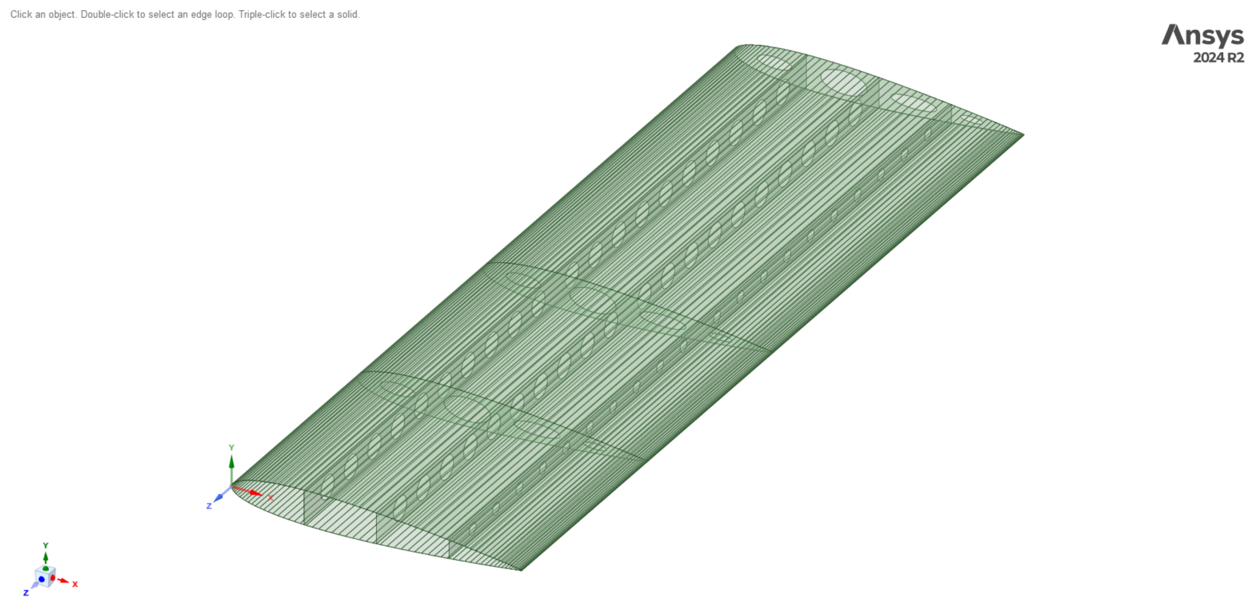


Figure 19: Spaceclaim Model Geometry with Holes in the Ribs and Spars

For this model, we put holes in both the ribs and the spars. Additionally the number of spars and ribs was increased to three. The spars are evenly spaced with one in the exact center, while the ribs are in the same place with the third one being centered between the fixed edge and the center rib. The idea behind this design is that adding holes decreases the weight such that adding more support has less of an effect on the weight, thus the skin thickness can also be less than with fewer supports.

The holes in the first two spars (from front to back) have a diameter of 0.4m, while those in the rear spar have a diameter of 0.2m. The holes in the ribs are elliptical so as to maximize their size based on the shape of the rib.

Ribs+Spars Holes, 0.1m Mesh Size, Optislang Optimized			
Top Skin Thickness	0.012652 m	**Mass**	7666.9 kg
Bottom Skin Thickness	0.012652 m	**Tip Deflection**	0.5168 m
Rib Thickness	0.00862024 m 0.00835729 m	**Max. Effective Stress**	228 MPa

	0.00810449		
Spar Thickness	0.0659994 m 0.0605009 m 0.00756228 m	**Factor of Safety**	1.58484

Table 11: Parameters of Lightest Short Aft Spar Geometry

ANSYS Results

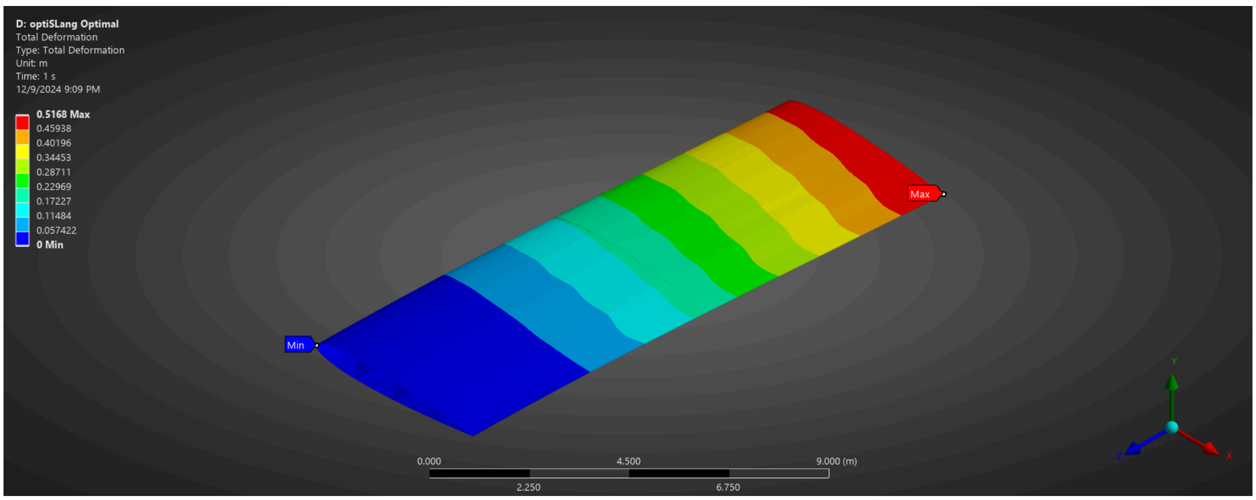


Figure 20: Total Deformation

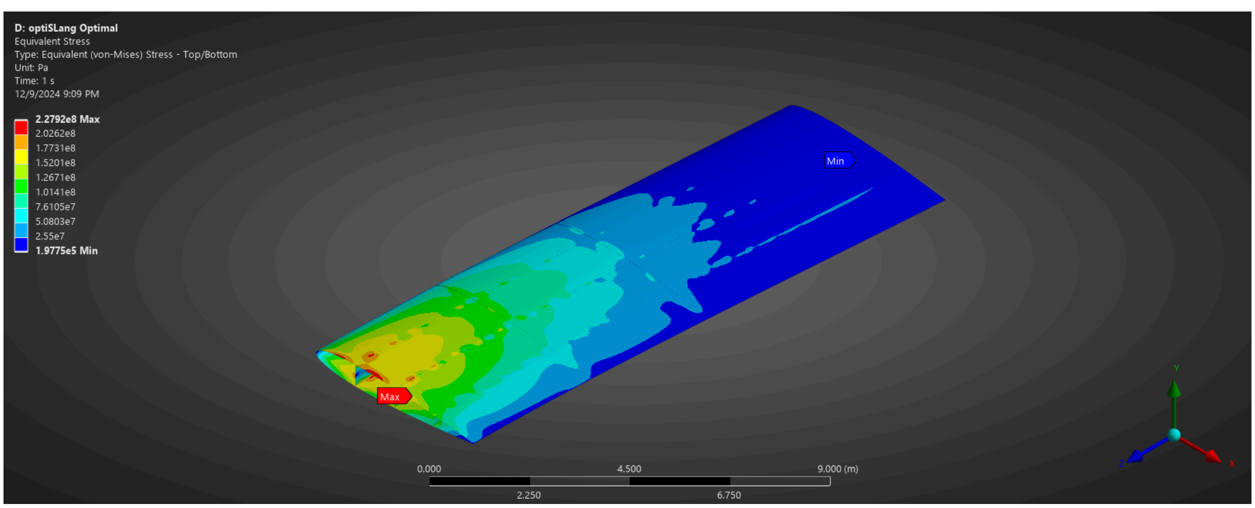


Figure 21: Equivalent Stress

Discussion

This design was able to significantly decrease the weight of our wing. What is interesting about this is that a large part of the weight savings actually come from the decreased skin thickness, and not the holes. However, the decreased skin thickness comes from having more spars and ribs, which is only possible—while maintaining a low weight—due to the holes in these supports. Unfortunately, the tip deflection of this design exceeds the maximum tip deflection set by the project constraints. So although we can not use this design as our final design, it shows that adding holes to the ribs and spars can open up the possibilities for rib and spar placement and quantity, which also may allow for a decrease in skin thickness. Furthermore, this design seems to create a stress concentration at the connection between the spars and the fuselage, leading to potentially inaccurate data and necessitating some level of mesh refinement as discussed earlier in the report.

Additionally, we found that the spar thickness of the rear spar is significantly lower than the thicknesses of the other spars. This could indicate that spar placement could be an interesting variable to experiment in the future, because if the rear spar were removed—if we deemed it negligibly thin—then the remaining spars would be moved forward relative to design 1.

Comparison of Design Options

Of the designs we've generated so far, purely in terms of our mass-minimization criterion, it seems that our most performant design is Design 3, specifically our Optislang-generated design:

Spars With Holes, 2500 Pa Bottom Surface Pressure, Manual Optimization + Optislang			
Skin Thickness	0.017801 m	**Mass**	8050.4 kg
Rib Thickness	0.0036804 m	**Tip Deflection**	0.37156
Spar Thickness	0.01 m	**Max. Effective Stress**	208 MPa
Wing Tip Thickness	0.0056042 m	**Factor of Safety**	1.81

Table 8: Parameters of Spars-With-Holes Geometry After Manual Optimization and Optislang

While our objective was simply to minimize the wing's mass, which we now have done, there's much more that can be discussed regarding the feasibility of each of our designs and their further development potential. For starters, it should again be clarified that our Optislang optimization was not exhaustive, and it's very much possible that, given more time or better refinement of the design space, the optimization process could've discovered new minimization pathways that altered our final result. However, given that Design 3's mass is around 400 kg less than the next best design (4), it seems reasonable to say that Design 3 is very likely to be our best-performing geometry in terms of mass efficiency.

While our group wasn't tasked with analyzing the cost of the wing, it is interesting to consider in tandem with the mass criterion. To a first approximation, the cost to make any of these wing designs in reality should be expected to be proportional to the mass of each design, simply accounting for the cost of the materials involved. However, the more extreme our design variations are, the more relevant the costs of the specific manufacturing processes involved will be. This is likely best illustrated by Design 3: while having the lowest mass, and thus the lowest direct material cost, many manufacturing processes that would bring the design to life would involve removing material from the spars, which increases the cost by adding unused waste material and significantly altering the manufacturing process relative to the other designs, which only use trimmed sheet metal of various thicknesses. The same can be said of any Design 2 variation that uses differing thicknesses for each portion of the skin, as getting multiple unique sheet metal thicknesses from a manufacturer would be more expensive than buying one uniform sheet in bulk.

The trade-off between mass and cost is a bit beyond our ability to discuss in this project. Thinking about it in terms of some aerospace business, the relative importance of having a lower wing mass versus having wings that are cheaper to manufacture is dependent on how long the wing is expected to be in service, fuel costs, plane efficiency, profits from operation, and many other factors that we could only roughly approximate at best, or guess at worst. Thus, we'll leave our analysis here: using spars with holes definitely seems like the best approach to mass minimization of the designs we've tested, though if costs are a factor, the discussion gets much more complicated very quickly.

Conclusion and Future Work

While our design iterations are not exhaustive explorations of all of the different options available to us to maximize the performance of the given wing geometry, we believe that our results thus far give us a strong grasp of the effects of the key design variables on the wing's performance characteristics. For example, the skin thickness contributes the most to the weight of the structure versus the thicknesses of the spars and ribs, whereas spar and rib thickness contribute to the distribution of stresses.

To continue with this version of the project, it would be interesting to explore the possibilities with holes. As our design 3 makes use of them and we learned some interesting results from design 6. It could be fruitful to attempt varying hole size to push the limit of the lack of structural support provided by the spars in design 3. It could also be interesting to experiment with inconsistent hole placement to decrease weight while still providing structural support. We also know that the skin is usually the heaviest part of the wing, so following design 3, 5, and 6 it would likely be smart to experiment with light methods of support placed strategically to allow for the decrease of skin thickness while maintaining low deflection.

Future work may include refining geometry to include more components such that it is more representative on a true aircraft wing (fasteners where the wing connects to the fuselage, flaps/ailerons, etc.). Furthermore, a higher range of loading cases may be tried to understand wing performance under different flight conditions than steady-state cruising, namely takeoff and landing. These geometric and loading cases will necessitate FEM refinement, including different and potentially variable boundary conditions.

Appendix: Team Member Contributions

Lola Anderson

Wrote the Geometry, Potential Energy, and Shell Elements and DOF Sections of Mathematical Model and Numerical Solution Strategy. Designed and completed analysis and OptiSlang for and wrote discussions for Designs 4 and 5. Completed and discussed mesh refinement for Design 1.

Adhyan Prasad

Wrote the introduction and assisted Lola with the Mathematical Model and Numerical Solution Strategy sections of the report. Completed initial geometry setup, mesh refinement, and first iteration of manual/automated optimization using optiSlang. Initiated group communication and scheduled work sessions and group tasks/deliverables.

Patrick O’Connor

Based on Adhyan’s initial geometry, designed and optimized Designs 2 and 3 (manually and using Optislang). Wrote the sections for Designs 1, 2, and 3. Analyzed all designs to compare them and recommend the best out of them. Partly contributed to conclusion section.

Noam Werners

Built, designed, and optimized Design 6. Wrote the section for Design 6. Analyzed results and comparison to contribute to the future work section.