# B-2 Style Flying Wing Design and Analysis

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# Agenda and Method of Approach

1. Topic Intro and Problem Statement
2. Research and Assumptions
3. Loading and Programming Analysis for Beam Types
4. Design of Model
5. FEM and CFD Analysis of Model
6. Conclusions and Lessons Learned

# Topic Introduction

Being deeply interested in the cutting edge of Aerostructures and their design, the group decided to analyze the Flying wing.

Northrop YB-49

**What is a Flying Wing aircraft?**

“A flying wing is an aeroplane that has no definite fuselage or tailplane, with its crew, payload, fuel, and equipment housed inside the main wing structure” (Wikipedia)

Theoretically, it is also the lowest drag design possible for an aircraft with fixed wings.

# Problem Statement and Initial Research

To explore the strange and cutting edge Flying wing, the group will choose an existing Flying Wing Aircraft to emulate. Following research and preliminary analysis the group will design a Flying Wing Aircraft structure to analyze. After 3D printing a real model of the design, the group will complete a more in-depth analysis of the model to explore and better understand how the topics learned in Aerostructures and Materials relate to the Flying Wing Aircraft type.

Northrop Grumman B-2 Spirit

We based our design off the B-2 Spirit, a prolific stealth bomber and the most Iconic Flying Wing aircraft.

# Deeper Background Research for Our Design

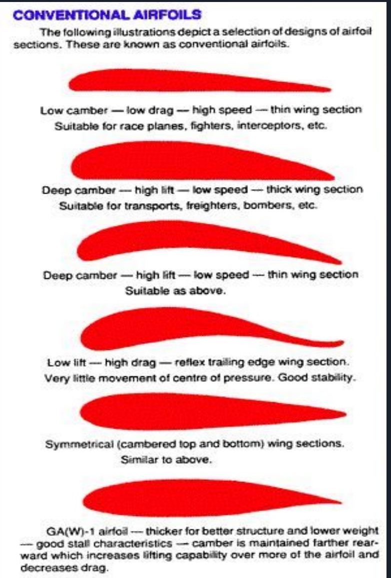
Flying wings have major design issues that must be addressed to justify pursuing the airframe type in the first place.

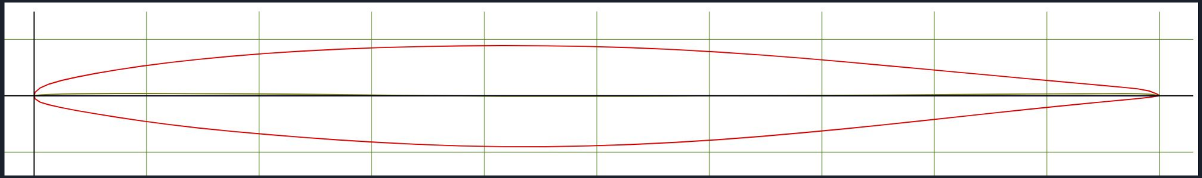
The most prevalent issue is to fit all of the typical aircraft components into the craft without creating a massive frontal area and ruining the “theoretically optimal” drag that the flying wing promises. Many designs make pods and fins to account for operational equipment (including crew). This is accomplished by having a very thin wing and a streamlined fuselage that blends seamlessly with the rest of the wing.

We try to emulate this principal in our own designs, even shelling the fuselage region for a better FEA analysis.

# Research for a More Informed Design

- Common Airfoil Choices for Flying wing and Tailless Aircraft :
  - Symmetrical
  - Dolphin Fin
  - Reflexed
- We decided based on how common the Dolphin Fin and the Reflexed airfoils are in Flying Wing Aircraft to design an airfoil shape which combined the two.
- We also found that the "Fuselage" of most Flying wing aircraft are an airfoil themselves and must be streamlined to the aircraft to generate additional lift and remain close to the lowest theoretically possible drag ideal that the Flying Wing design promises.



# Additional Airfoil/Cross section Research

Since there is a need to make space for operational equipment in a real B-2, getting a Supersonic capable airfoil shape streamlined to a fuselage has never been done. For example, the B-2's max speed is 628 mph. This means we must look at the common airfoils used in flying wing designs that we mentioned on the last slide.

Finding the optimal cross section will come with actual analysis but our preliminary choices are:

- I beam
- Z beam
- T beam

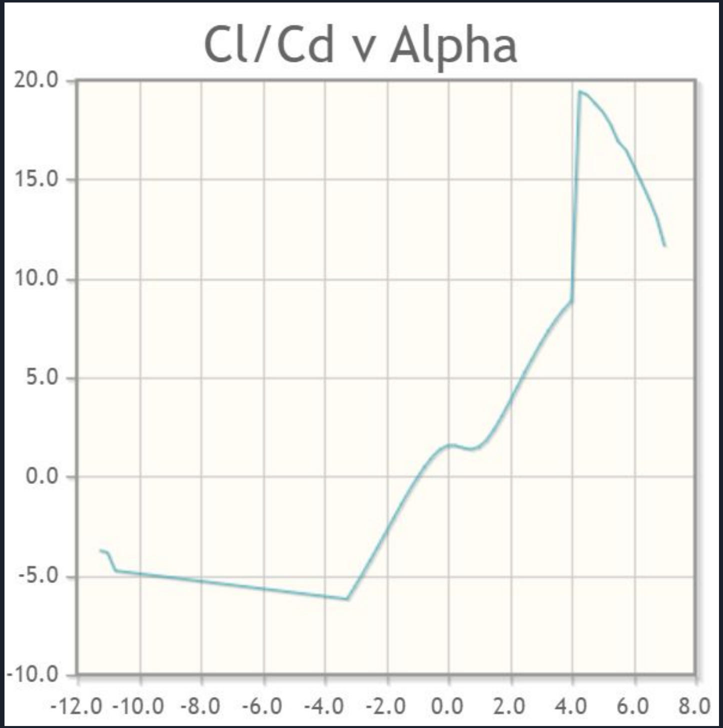
We will make our cross section choice based on strength, and then weight/volume.

# Assumptions

- In our calculations and analysis we assume:
  - Airfoil : dh4009sm
    - “Dolphin Fin”
  - Our material is homogenous PLA, neglecting any support
  - Typical 2D aerodynamic assumptions
  - Neglecting Skin of model’s wing during FEM and Cross sectional analysis since it’s incredibly thin

# Loading for Analysis

- Average chord, c = 0.3125 ft
- Span, L = 0.385 ft
- Wing Surface Area: 29.79in^2, Airfoil Area: 0.75in^2
- For dh4009sm airfoil at STP with:
  - Free stream velocity, U = 25 fps
  - And angle of attack, $\alpha = 4^0$
    - Coefficient of lift, $C_l$=0.2079
    - Coefficient of Drag $C_D$ = 0.02343
- Lift per unit span = 0.047 lbf/ft (0.223 N)
- Shear Modulus (G) = 2.4 GPa
- Young's Modulus (E) = 4.107 GPa



# Programming Analysis

- Created modules containing the following functions:
  - Centroid
  - Sectional properties
  - Torsional rigidity
  - Singularity functions of a distributed loads
    - Shear
    - Moment
  - Normal stress
  - Deflection
- Goal:
  - Want to choose the stiffest beam
    - High torsional rigidity
    - Least amount of deflection

# Programming Calculations

```
BELOW ARE ALL VALUES WITH RESPECT TO THE I CROSS-SECTIONAL AREA
c1 = [0.25  0.395] c2 = [0.25 0.21] c3 = [0.25  0.025] c = [0.25 0.21]

Ixx = 0.0018582000000000004 in^4; Iyy = 0.001045 in^4; Ixy = 0.0 in^4

Torsional rigidity = 38.50000000000001 lb in^2

Shear singularity function =
-0.05·z

Moment singularity function =
        2
-0.025·z

Double int moment singularity function =
                      4
-0.00208333333333333·z

Mx(z) =
        2
-0.025·z

sigma_z =
                  2
2.82531482079432·z

u = 2.19834642140859e-6*z**4 in  v = 0 in
THIS MARKS THE END OF ALL CALCULATIONS FOUND FOR I CROSS-SECTION
```

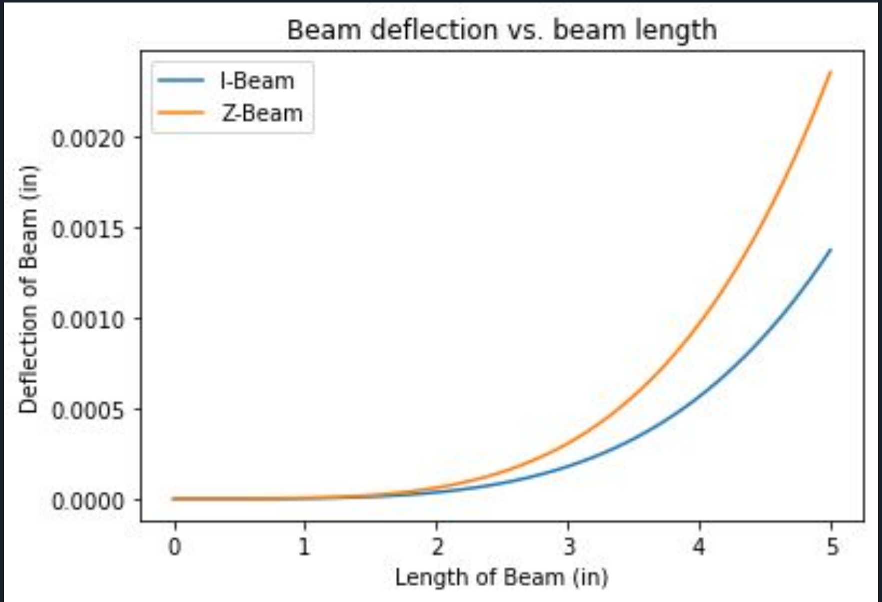
```
BELOW ARE ALL VALUES WITH RESPECT TO THE Z CROSS-SECTIONAL AREA
c1 = [0.25  0.395] c2 = [0.25 0.21] c3 = [0.25  0.025] c = [0.25 0.21]

Ixx = 0.0010834500000000003 in^4; Iyy = 0.00017664062500000004 in^4; Ixy = 0.0 in^4

Torsional rigidity = 26.833333333333334 lb in^2

Shear singularity function =
-0.05·z

Moment singularity function =
        2
-0.025·z

Double int moment singularity function =
                      4
-0.00208333333333333·z

Mx(z) =
        2
-0.025·z

sigma_z =
                  2
4.84563200886058·z

u = 3.77033302899205e-6*z**4 in  v = 0 in
THIS MARKS THE END OF ALL CALCULATIONS FOUND FOR Z CROSS-SECTION
```

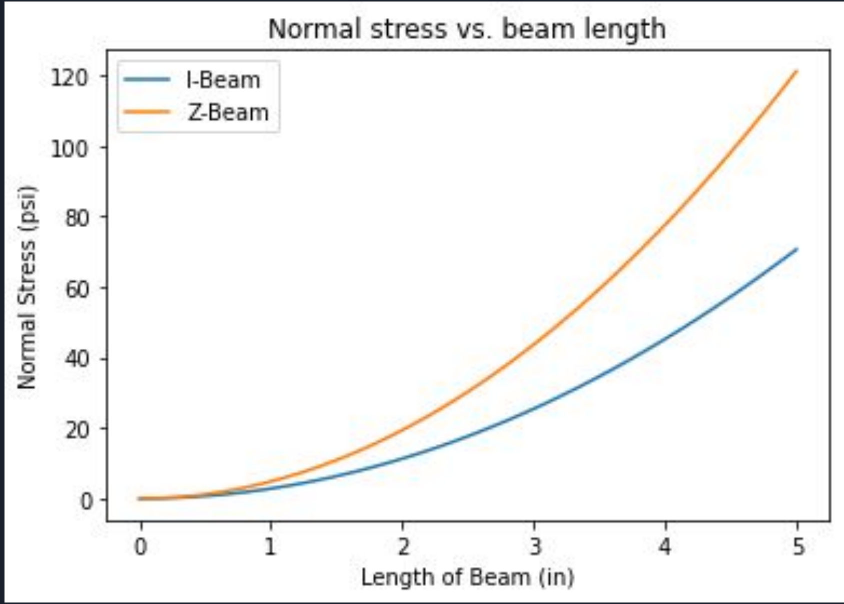
The calculations for the I and Z beams can be viewed in the images.

# Programming Results

I: $u = 2.198e\text{-}6z^4$ ; u(max) = 1.374e-3 in

Z: $u = 3.770e\text{-}6z^4$ ; u(max) = 2.356e-3 in




I: $\sigma_z = 2.825z^2$ ; $\sigma_z$(max) = 70.625 psi

Z: $\sigma_z = 4.846z^2$ ; $\sigma_z$(max) = 121.15 psi

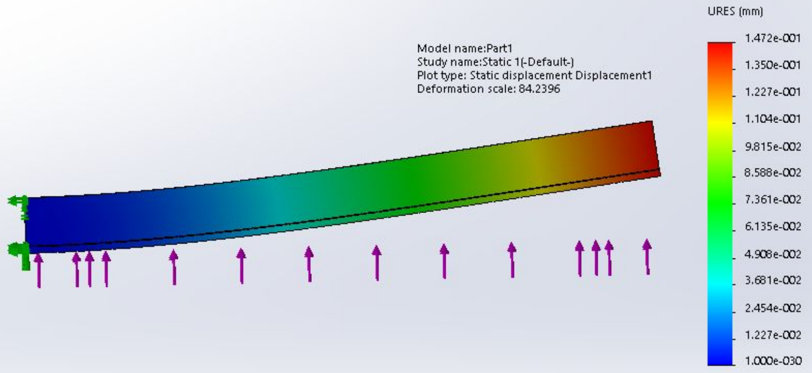
# Programming Results

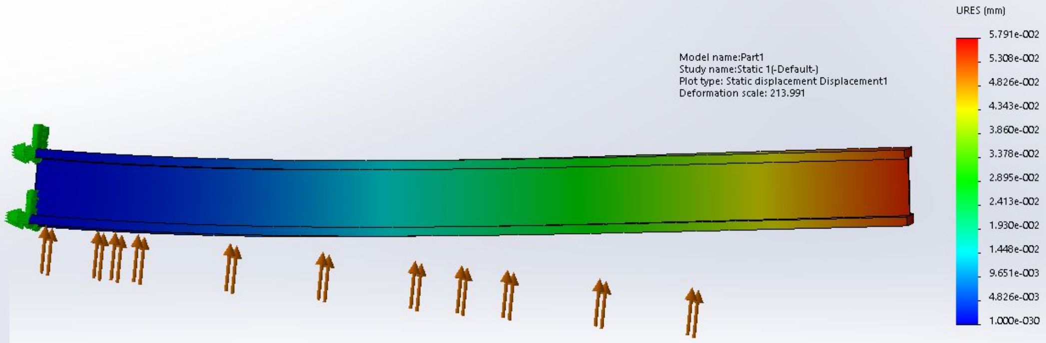
Ultimately, the I cross-section better suits the team’s needs compared to the Z cross-section.

The I cross-section has a larger torsional rigidity, smaller amount of deflection, and lower concentrated stress in comparison to the Z cross-section; therefore, the team will move forward using the I cross-section over the Z cross-section.

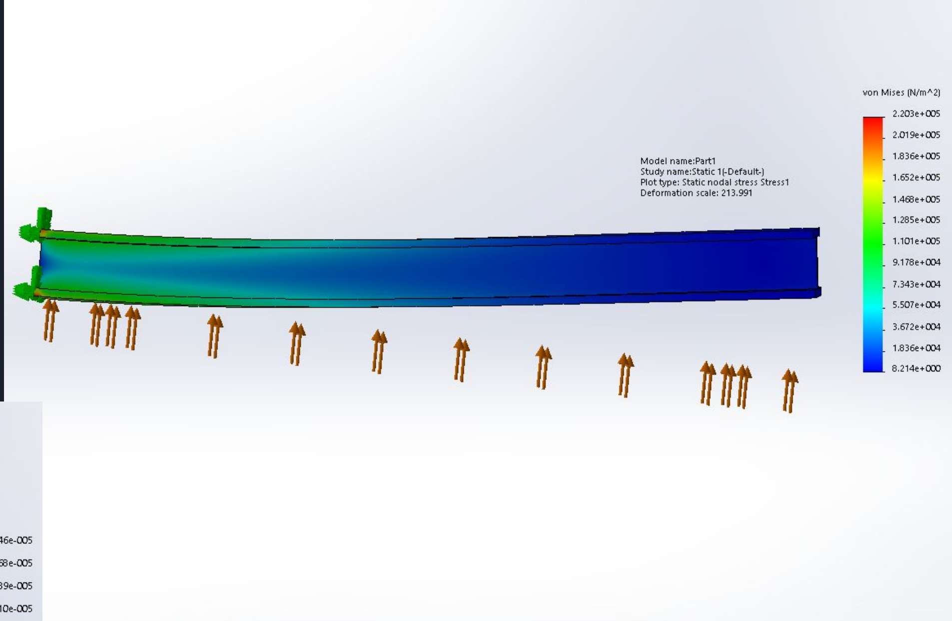
(Reference for understanding code: click here)

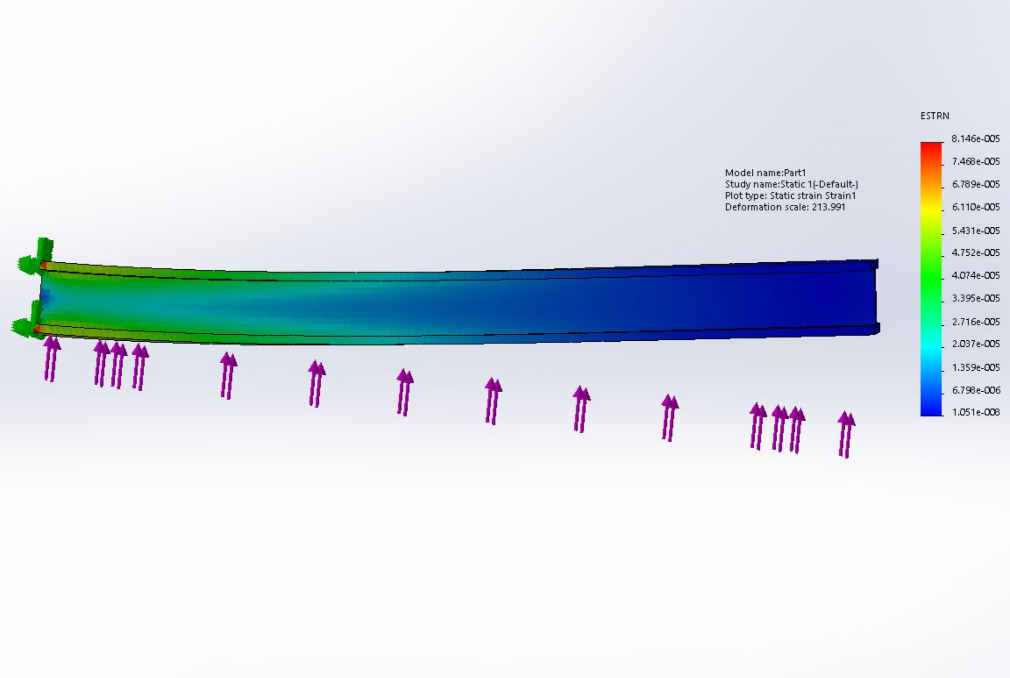
# Cross Section Analysis of the Spar



# Stresses/Strains on the Spar



# Spar FEM Results

- I Beam vs T Beam deflection under 0.3N Lift Force:
  - I Beam deflection = $5.8 \times 10^{-2}$mm
  - T Beam deflection = $1.47 \times 10^{-1}$mm

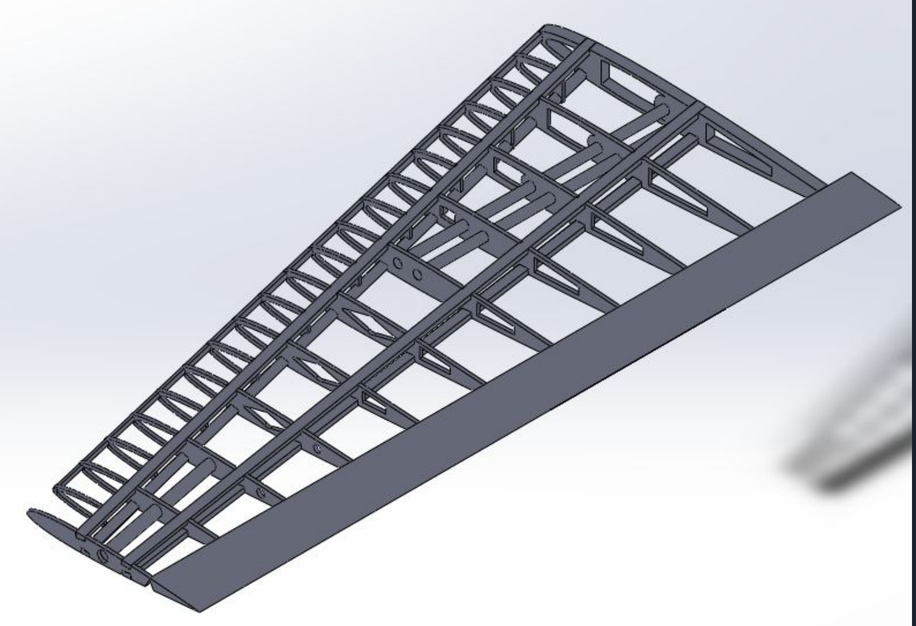
This shows the I beam should be used as a spar for the wing since it is a significantly stronger structure

- Max Von Mises Stress on the I Beam = 0.2203 mPa

Lift Force  is found out as 0.018 lbf through hand calculations

# Design Challenges

The biggest design challenge we faced along with the unusual shape of the B2 wing was to make it thick enough to be 3D printed. We failed our first few prototypes because the wing design was too thin and complex to be 3D printed.

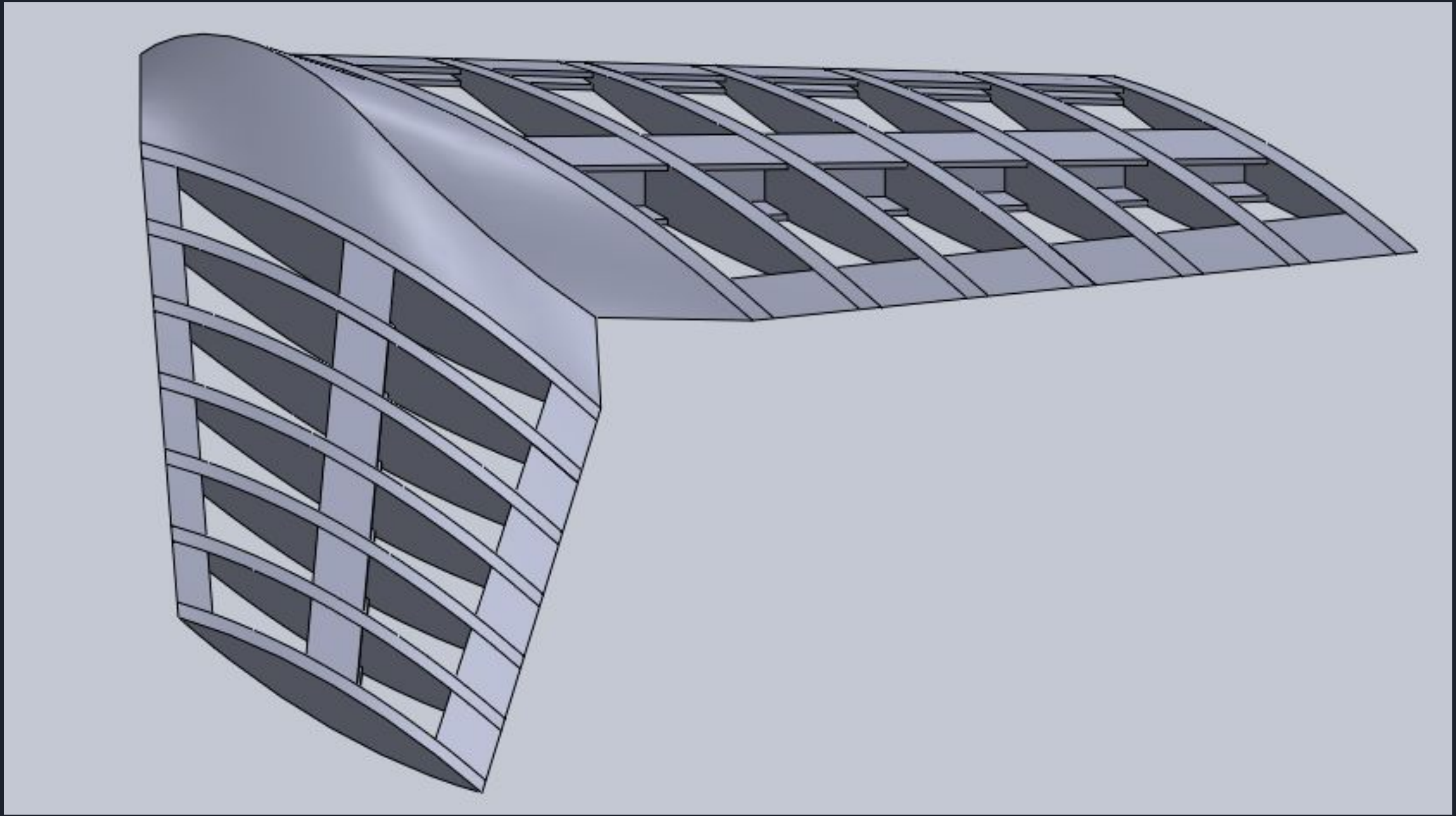


# Design Challenges Continued

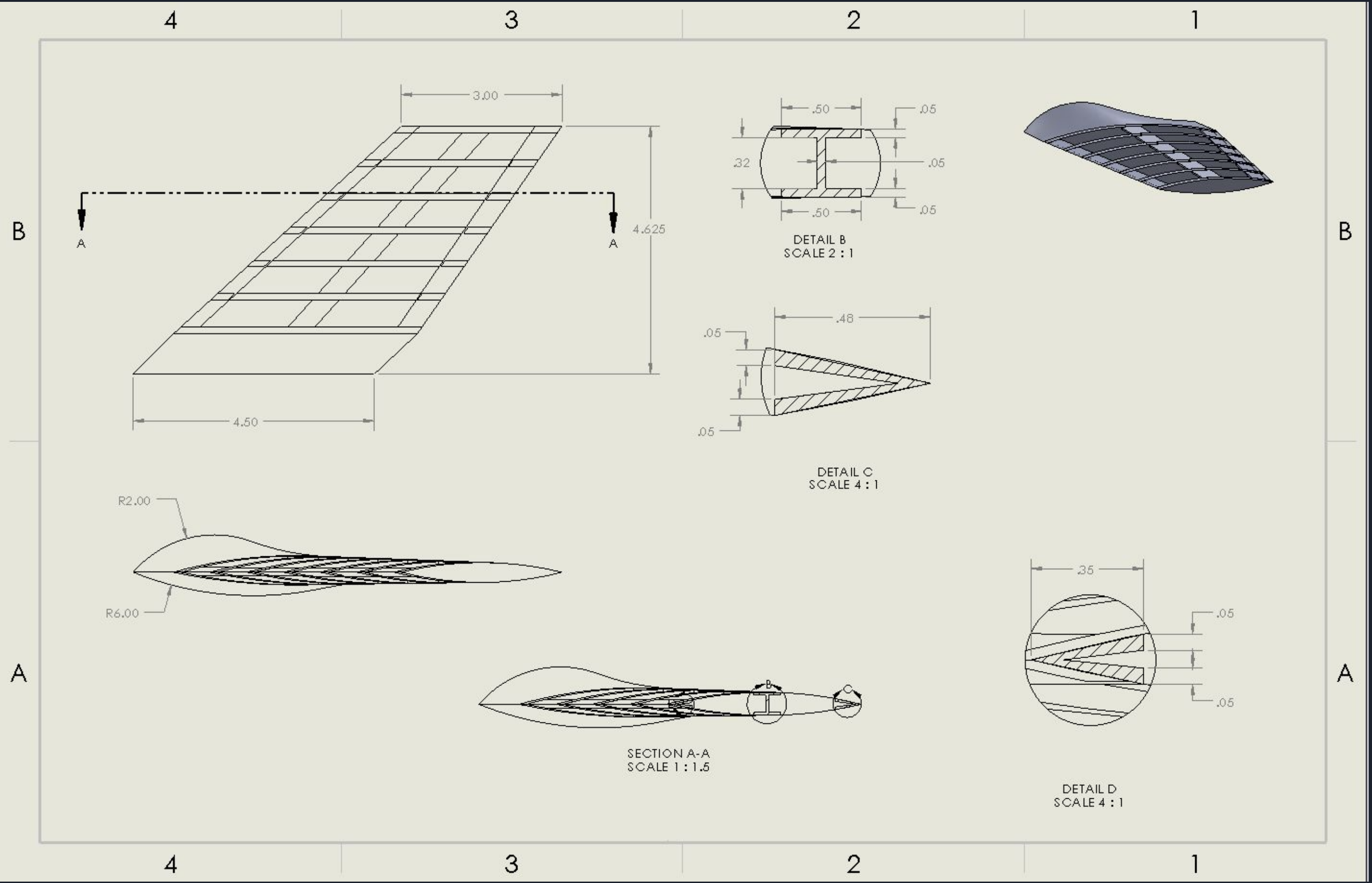
Our initial problems as stated on the last slide,  was largely due to the complexity of the earlier models and its compatibility with additive manufacturing techniques. When a part like a wing is printed, “floating objects” like the tips of the wing or the spars need supports to be printed along with them to ensure the plastic goes in the correct place and does not fall from the nozzle or collapse mid-print. Our supports were in the correct positions and our slicing was correct, however when removing the parts from their supports, the thin walled members were still too thin. They would snap and get stuck to the supports when removing the rest of the part which was larger and thicker.

We learned quite a bit as a result of our iterative design process and ended up with a much more compatible final model.

# CAD Model



# CAD Drawing Showing Wing Cross Section



# Manufacture of Model

Printing the Body and the thin walled cross sections took a few iterations to get right, since thin members tend to print poorly in the high tolerance printers of the Forge. In the end we went with an I beam and two bracket beams to solve our issues, instituting a uniform thickness of .050".  We also needed to print in pieces and assemble the parts to create the full body.

Future work:

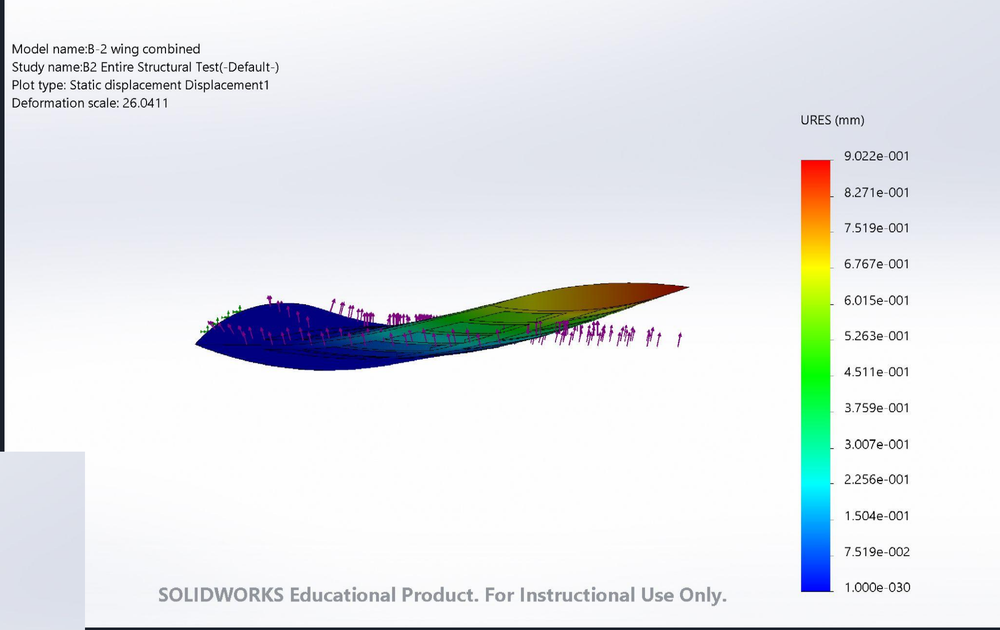
We plan to make a second model laser-cut from balsa wood, with a skin for the wings made from a purchased membrane. We will also proceed with further analysis then.

# Full Model FEM

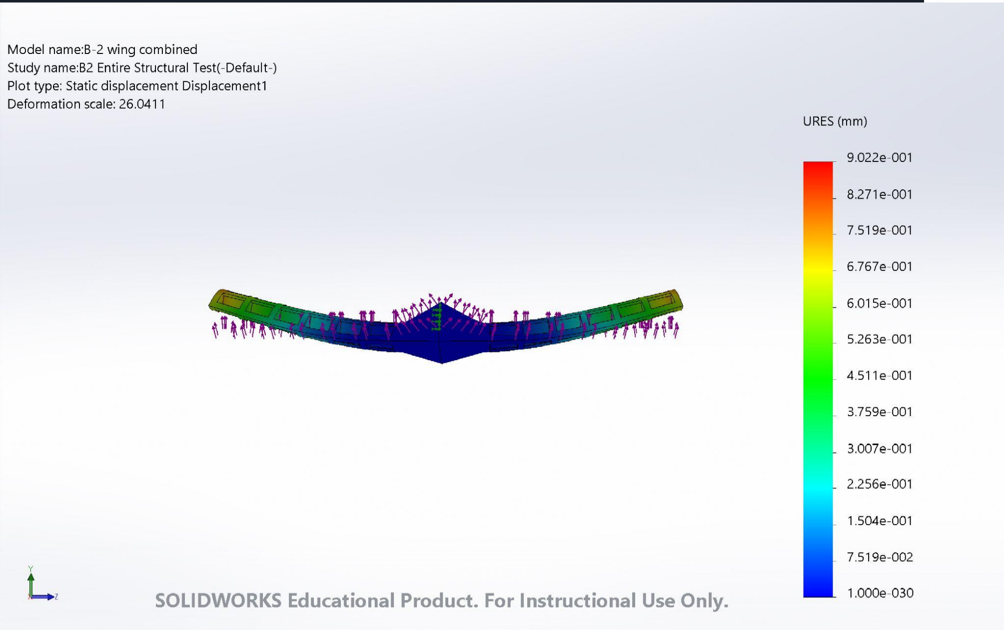
- Used the calculated distributed load of about 0.05 lbf/span
  - Fixed the centerline of the model
  - Applied the load on the main spar, leading/trailing spars, and central body

- Real model was 3D printed with PLA
  - SolidWorks doesn’t have PLA in its material library, but does have ABS
  - PLA is stronger than ABS, if FEM shows the ABS won’t yield, PLA shouldn’t either

# Deflection



Model name:B-2 wing combined
Study name:B2 Entire Structural Test(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 26.0411
URES (mm)
9.022e-001
8.271e-001
7.519e-001
6.767e-001
6.015e-001
5.263e-001
4.511e-001
3.759e-001
3.007e-001
2.256e-001
1.504e-001
7.519e-002
1.000e-030
SOLIDWORKS Educational Product. For Instructional Use Only.

Model name:B-2 wing combined
Study name:B2 Entire Structural Test(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 26.0411
URES (mm)
9.022e-001
8.271e-001
7.519e-001
6.767e-001
6.015e-001
5.263e-001
4.511e-001
3.759e-001
3.007e-001
2.256e-001
1.504e-001
7.519e-002
1.000e-030
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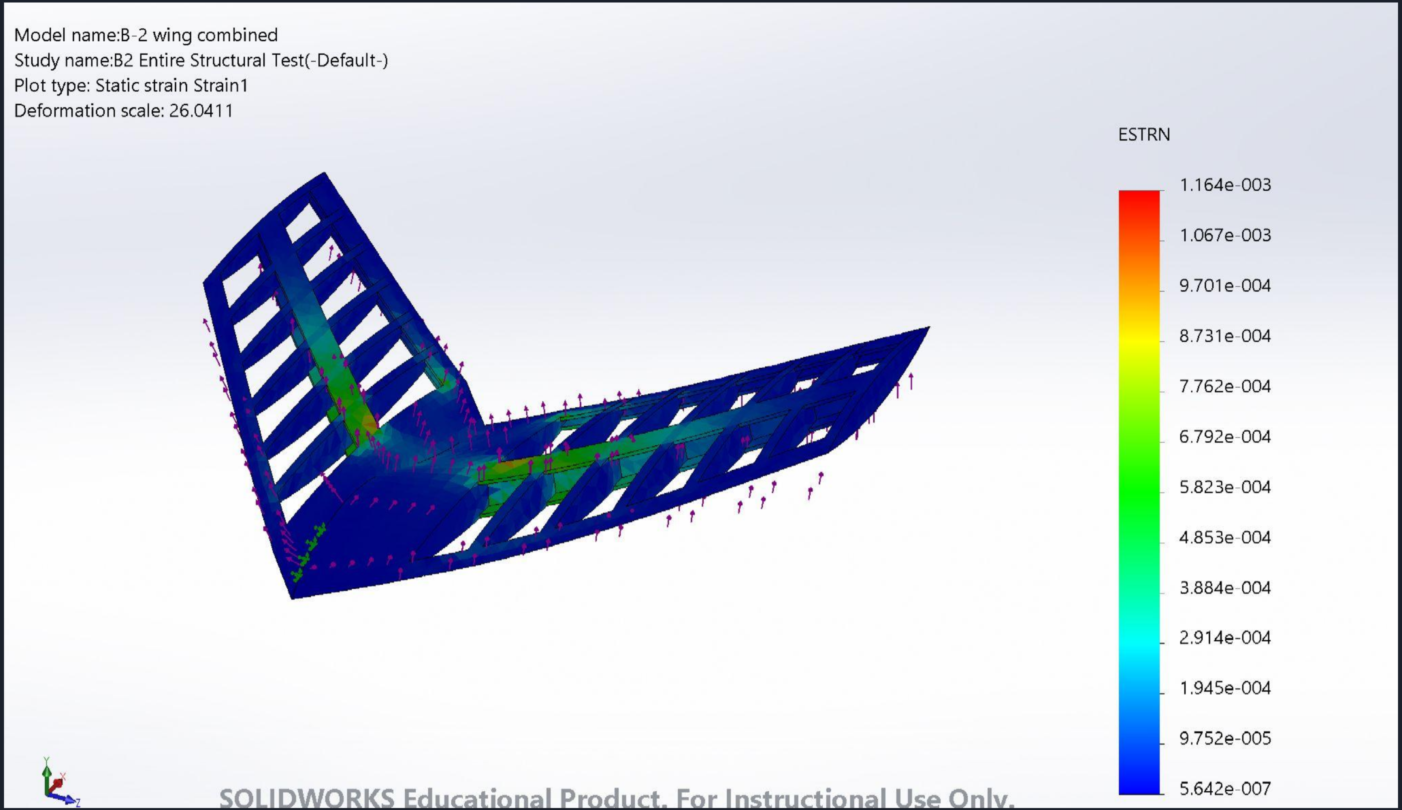
# Strain


Model name:B-2 wing combined
Study name:B2 Entire Structural Test(-Default-)
Plot type: Static strain Strain1
Deformation scale: 26.0411
ESTRN
1.164e-003
1.067e-003
9.701e-004
8.731e-004
7.762e-004
6.792e-004
5.823e-004
4.853e-004
3.884e-004
2.914e-004
1.945e-004
9.752e-005
5.642e-007
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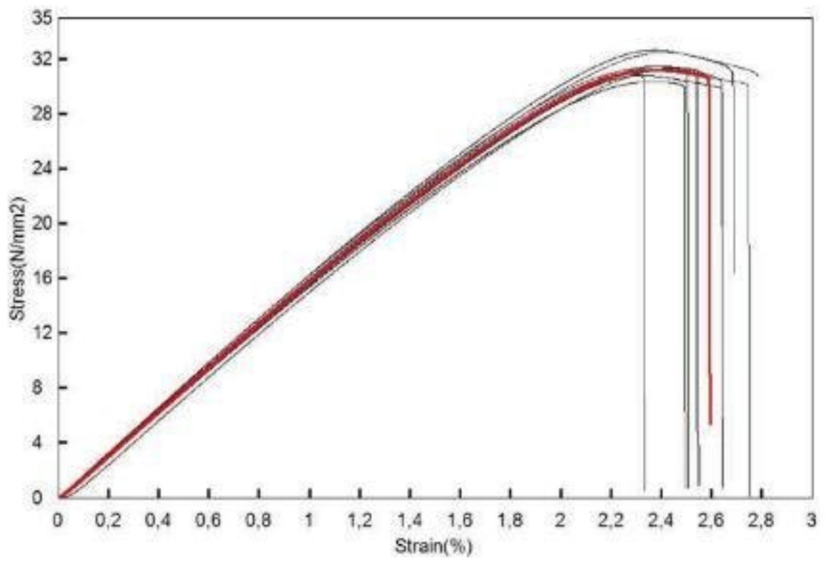
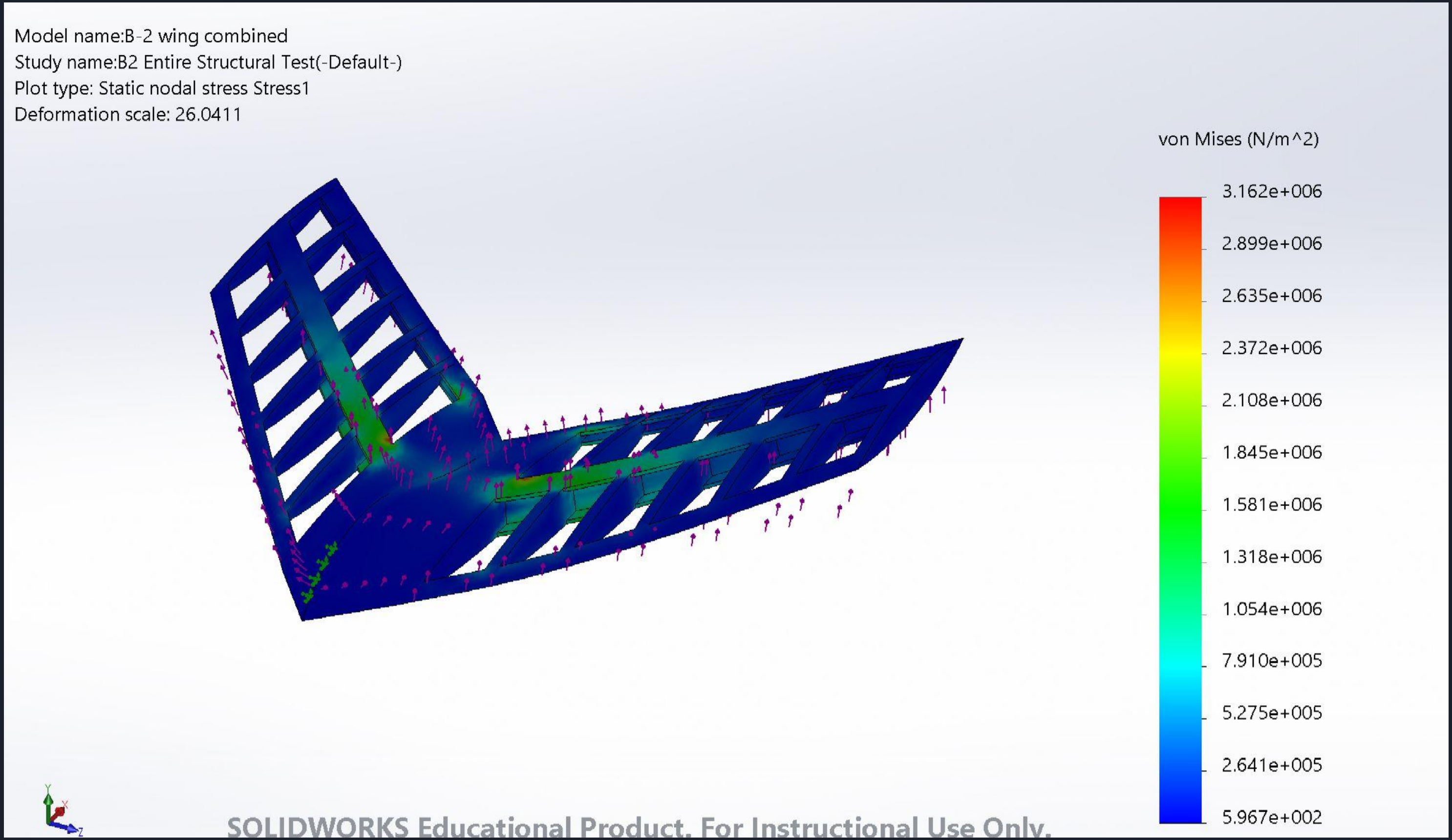
# FEM Deflection and Strain

- Max Deflection was approximately 1mm
  - Located at the tip of the trailing edge
- Reasonable deflection, and not enough to warrant structural or aerodynamic concern
- Max Strain was 0.001164
  - Located at the root of the central spar and on the trailing side
  - Well within the elastic region for both ABS and PLA
    - No need for concern




a) Stress-strain curve of ABS and b) stress-strain curve of PLA thermoplastic material

# Stress


Model name:B-2 wing combined
Study name:B2 Entire Structural Test(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 26.0411
von Mises (N/m^2)
3.162e+006
2.899e+006
2.635e+006
2.372e+006
2.108e+006
1.845e+006
1.581e+006
1.318e+006
1.054e+006
7.910e+005
5.275e+005
2.641e+005
5.967e+002
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# FEM Stress

- Max Stress was about 3 MPa
  - Located at the same place as max strain

- PLA Yield Strength: 26 MPa:
  - F.S. = 8.2
- ABS Yield Strength: 22 MPa
  - F.S. = 7

# FEM Takeaways

- No yielding for either material
- Can likely optimize material distributions for lighter weight while maintaining high factor of safety
- Stresses and Strains both carried mostly by the main spar, as intended

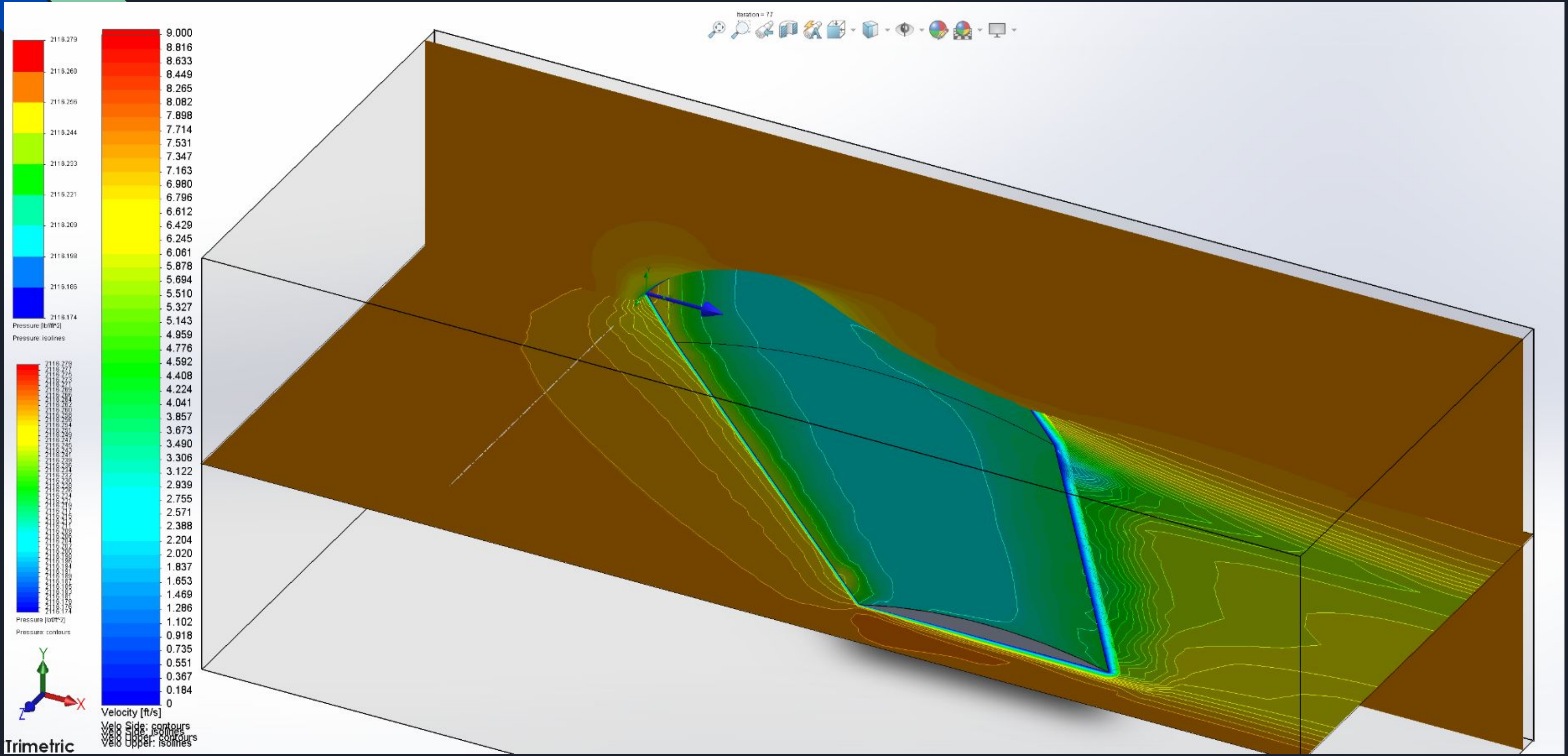
# Half Model CFD

- CFD was done on one side of the model with skin covering the wing
- One simulation run at 0 degrees angle of attack
- Another simulation run at 4 degrees angle of attack
  - Same AoA for hand calculations

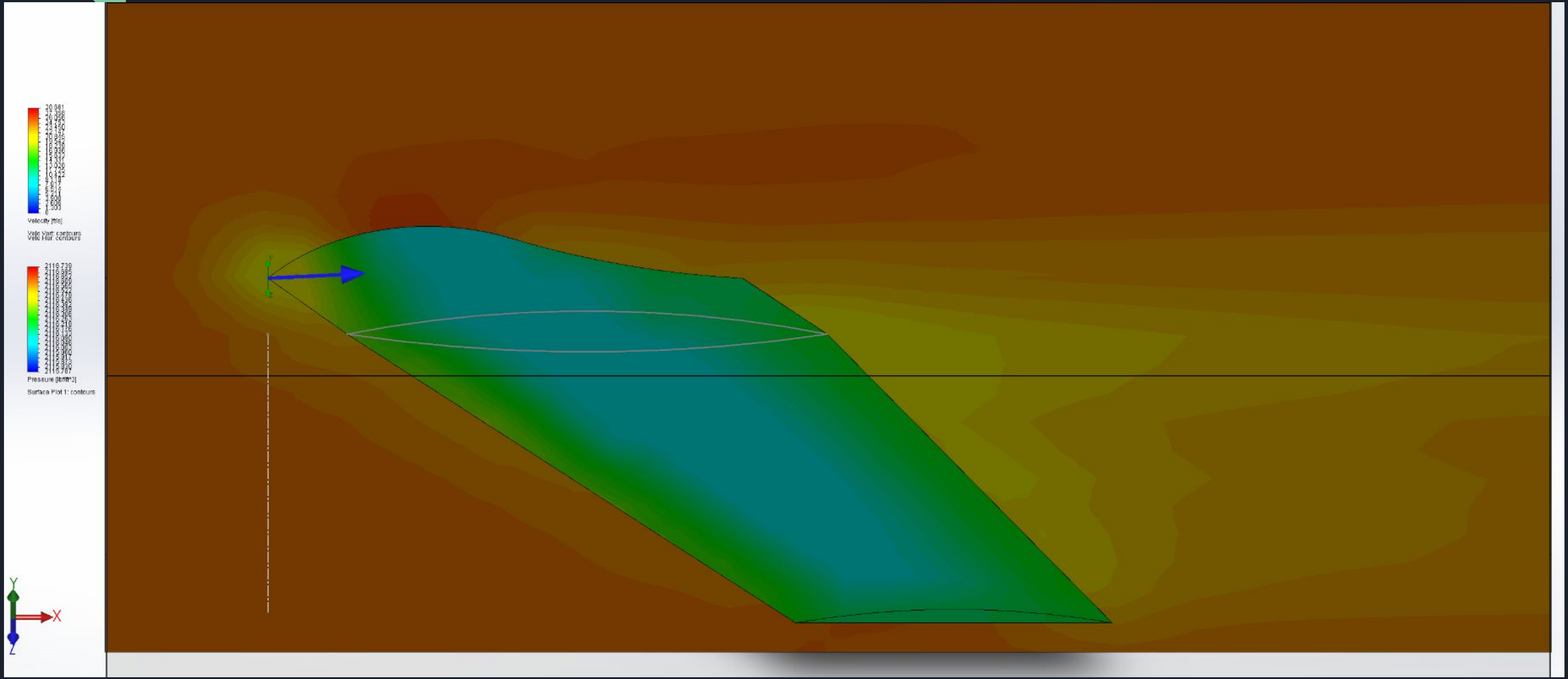
- Goals
  - See if the 3D printed model could generate enough lift to fly
  - Compare simulated lift force to calculated lift

- Gradients on vertical and horizontal cuts show velocity distribution
- Gradient on wing surface shows pressure distribution

# CFD 0 Deg AoA


Velocity [ft/s]
9.000
8.816
8.633
8.449
8.265
8.082
7.898
7.714
7.531
7.347
7.163
6.980
6.796
6.612
6.429
6.245
6.061
5.878
5.694
5.510
5.327
5.143
4.959
4.776
4.592
4.408
4.224
4.041
3.857
3.673
3.490
3.306
3.122
2.939
2.755
2.571
2.388
2.204
2.020
1.837
1.653
1.469
1.286
1.102
0.918
0.735
0.551
0.367
0.184
0
Velo Side: contours
Velo Side: isolines
Velo Upper: contours
Velo Upper: isolines
Trimetric

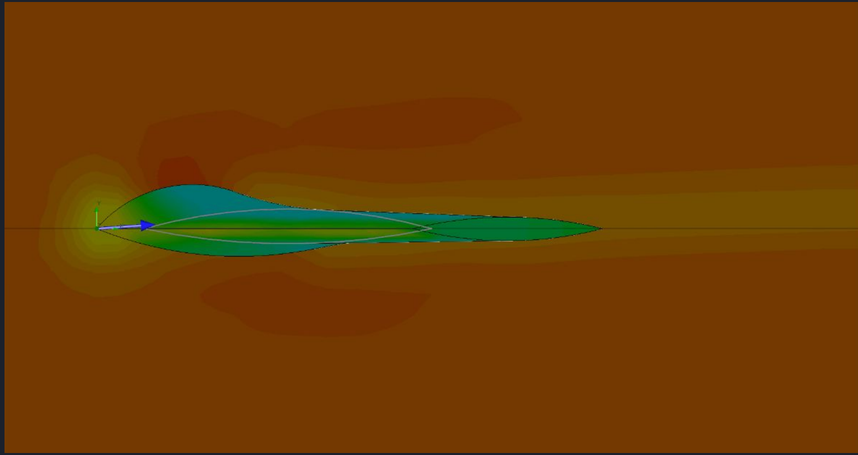
# CFD 4 Deg AoA



Velocity [ft/s]
Velo Vert: contours
Velo Hor: contours
2116.739
2115.767
Pressure [lbf/ft^2]
Surface Plot 1: contours
Y
X
Z

# CFD Results

- For 25 fps:
  - 0.0073 lbf Lift
  - 0.003 lbf Drag (very little!)
    - Confirmed Low Drag for Delta Wing



- Also low lift relative to overall weight
  - Need either a higher lift airfoil
  - Or even lighter material

- Compared to 0.018 lbf calculated with assumptions
- For future analysis
  - Increase velocity to achieve dynamic similarity with full size aircraft

# Conclusions and Lessons Learned

- With PLA, our I beam and “<” cross sections proved very effective, able to hold considerable loading.
- Our theoretical analysis is consistent with the FEM we did on the model as well.
- These cross-beams also made the  model incredibly lightweight (even for 3D printing)
- We learned also that the I beam in the center took on a majority of the loading for the model, which coincides well with the theory we learned in class.
- Additionally we learned how to design for 3D printing, which is a whole side of design engineering full of nuance and challenges.

# Works Cited


http://airfoiltools.com/airfoil/details?airfoil=dh4009sm-il

https://www.matweb.com/search/DataSheet.aspx?MatGUID=3a8afcddac864d4b8f58d40570d2e5aa&ckck=1

https://en.wikipedia.org/wiki/Flying_wing#:~:text=A%20flying%20wing%20is%20an,%2C%20booms%2C%20or%20vertical%20stabilizers

https://www.researchgate.net/figure/a-Stress-strain-curve-of-ABS-and-b-stress-strain-curve-of-PLA-thermoplastic-material_fig3_329481052

# Thank you all for your time!
# Questions?