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Optimization of Fuselage Design for a Sounding Rocket Using Composite Materials

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The Rocket Team at the Ohio State University has initiated project Prometheus to break an altitude record of 38,000 meters. The team plans to design and construct a two-stage boosted dart rocket with a scientific payload to achieve the goal. The rocket airframe will be constructed of composite components and will utilize novel construction techniques. In order to maximize the rocket's performance, a detailed analysis was performed to optimize the structure. A finite element method was used to analyze the static, buckling, and modal structural behavior of the airframe. A prototype was constructed to verify the results from the static structural analysis.

I. Introduction

The Rocket Team at the Ohio State University was started in 2004 with the fundamental goal of offering students an opportunity to practically apply their knowledge. The team consists of undergraduate and graduate students in multiple disciplines at Ohio State with the majority of members in engineering majors. We recognize the value of hands-on experience in the field of engineering, and serve to promote such an opportunity. The Rocket Team consists of roughly twenty members, with all operations coordinated by an executive committee. The team also functions under the oversight of a faculty advisor. A project, Prometheus, was started in an attempt to break an altitude of 38,000 meters by use of a two-stage boosted dart rocket concept. New design and construction techniques had to be created and implemented from the team's standard practices in order to complete this project successfully.

II. Design Overview

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The overall dimensions and configuration of the rocket design can be viewed in Figure 1. The vehicle consists of two stages, with the first stage constituting the first 2.18 meters and the second stage the remainder of the length. The second stage contains the boosted dart portion of the rocket and a structural section capable of containing a control system.

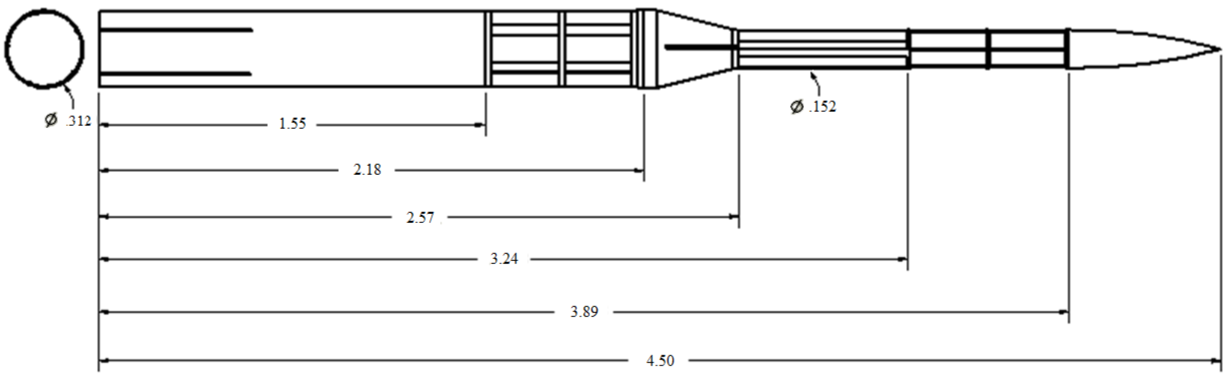

Figure 1: Prometheus Design Dimensions (in meters)

Common amateur rocket construction consists of several bulkheads mounted in a body tube, Figure 2, with the rocket motor being constrained by a bulkhead. This method would not

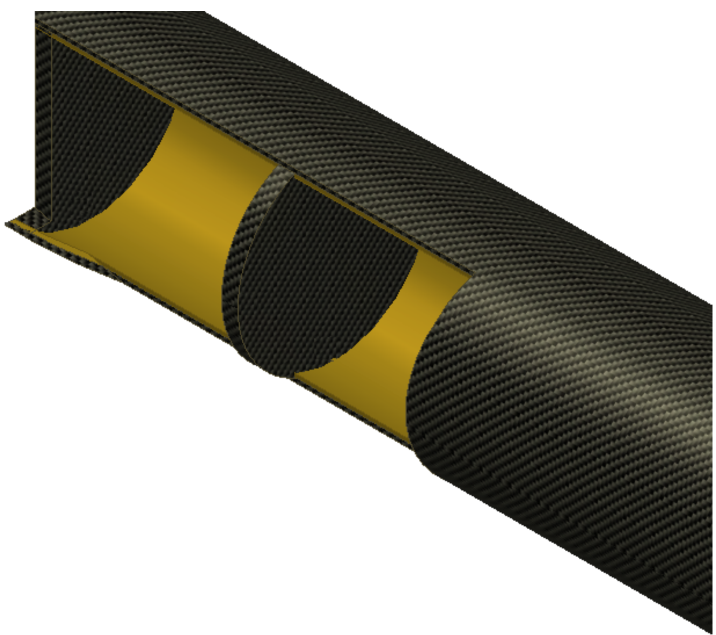

Figure 2: Traditional Amateur Rocket Fuselage

be a realistic choice due to the 210000 N-s impulse that is predicted for our first stage motor. The mounting of the bulkheads would be difficult and non-traditional if the previously used body tube and bulkhead system were to be used. A stringer and bulkhead system with a thin skin, similar to those used in commercial aircraft[3], was implemented in order to support the forces experienced throughout flight. This method also allows for direct access to the internal portions of the rocket without difficulty, as the panels acting as the skin are easily removable.

III. Materials

A material's maximum allowable stress, susceptibility to buckling, maximum temperature, cost, weight, and ease of use in assembly must be considered and analyzed to find the best choice for use in construction of the airframe.[4] Although expensive in comparison to candidate materials such as aluminum, steel, and other composites, carbon fiber in the form of a tri-directional weave was chosen as the material due to its superiority in the other considered aspects. In order to determine the composite's properties within the weave, a rosette was used. The materials single strand properties[5] were used and the angle off of a particular fiber in the rosette that gave the weakest property values was chosen to base the composite's overall properties. This enabled the accompanying analysis to have the worst-case scenario placed upon it. The resulting properties are displayed in Table 1.

Table 1: Material Properties

Density	1530 kg/m^3
Young's Modulus	179 GPa
Poisson's Ratio	0.0197
Tensile Strength	1.80 GPa
Compressive Strength	1.57 GPA

Temperature is this composite's main weakness. The epoxy begins to melt at 394 K. Since the skin of the vehicle will not be a key structural member of the airframe, any aerodynamic heating that will occur throughout the short period of flight can be neglected in the analysis. If the epoxy begins to melt on the skin it will cause rigidity of the skin to be lost but the internal structure will not be affected.

IV. Structure

The overall assembled internal structure for rocket is depicted in Figure 3. This structure

[5] http://www.toraycfa.com/pdfs/T1000GDataSheet.pdf

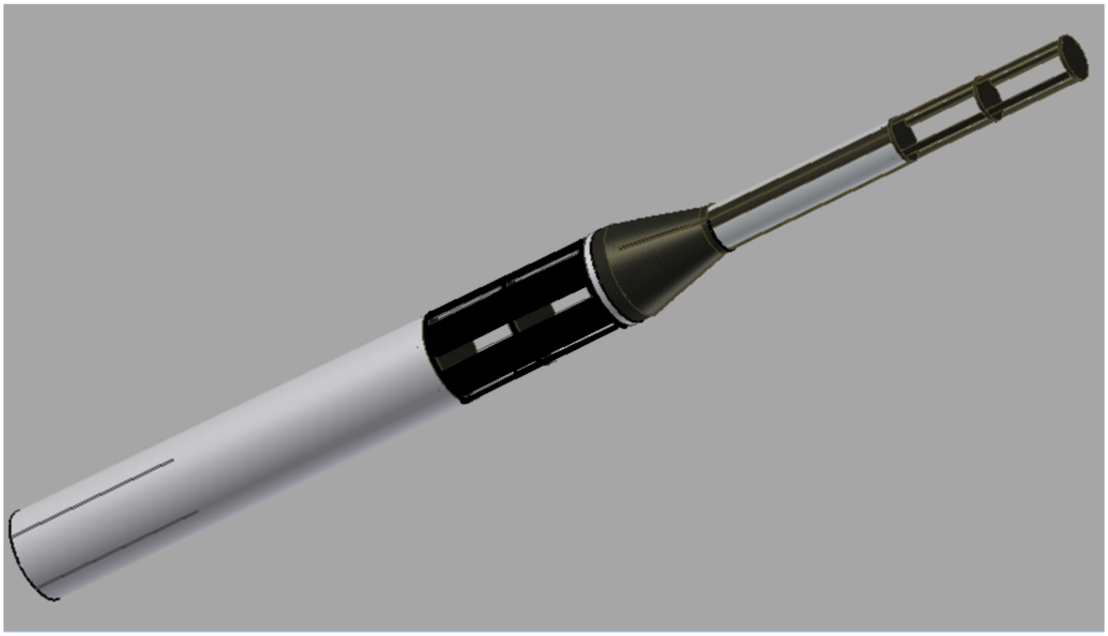

Figure 3: Internal Structure

would be covered by thin carbon fiber panels in the final stages of construction. The second stage's internal structure, Figure 4, attaches to the top of the motor. There is enough empty volume for a flight computer and control system to be installed. Due to the need to have sufficient empty space, it was deduced early on that this would most likely be the weakest structural segment of the vehicle. This assumption will be verified through analysis. This structure consists of four stringers and three bulkheads. The stringers are equally spaced in their location with respect to the bulkheads through which they are mounted.

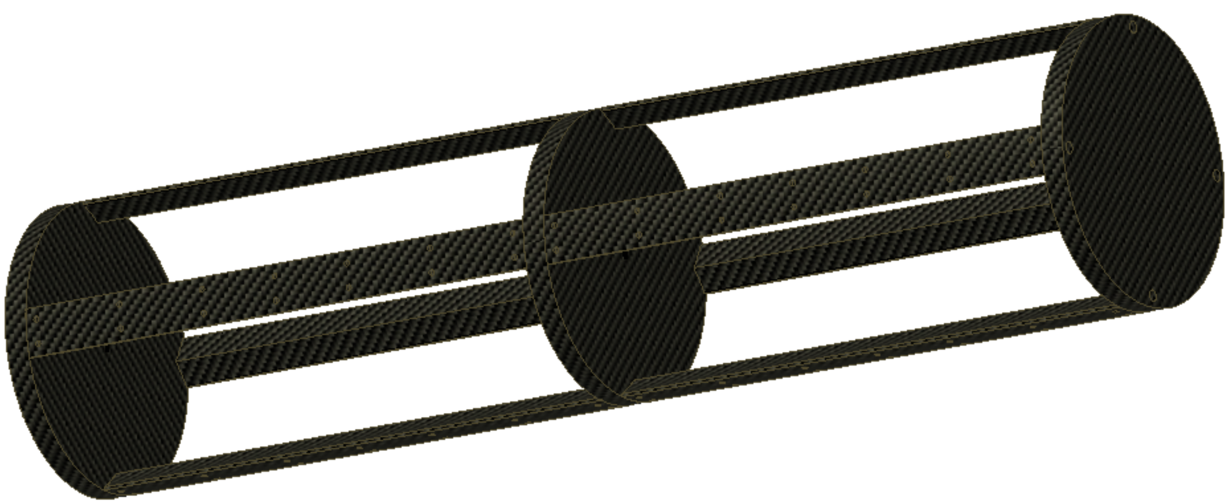

Figure 4: Second Stage Internal Structure

The first stage's internal structure, Figure 5, is similar to the second stage as it mounts to the motor. However, it has six stringers that are relatively thicker than those found on the second stage. There still remains an adequate amount of empty volume to allow for the installation of a recovery system and any required avionics package.

Figure 5: First Stage Internal Structure

The final element to both of the stage's structure is the motors. The second stage motor will structurally be a commercially supplied aluminum casing with modifications to allow for mounting. The first stage motor is being designed by the members of the Propulsion Team. The casing will be constructed of aluminum and will be machined to a thickness of 8.89×10^{-3} m. During the launch, the motor will place a load of 11,000 N on the rocket structure. This will result in a maximum loading of approximately 6 G.

V. Loads

In order to effectively analyze the vehicle, loads and constraints had to be properly placed to simulate the correct behavior of the structure. To simplify our problem, we are assuming that no lift will be created on the body. This would suggest a vertical flight path, which is possible when the control system is integrated into the design. The drag and thrust were placed as shown in Figure 6. A constraint was placed on the exhausting end of the motor in order to be able to have a good representation of a static model.[6]

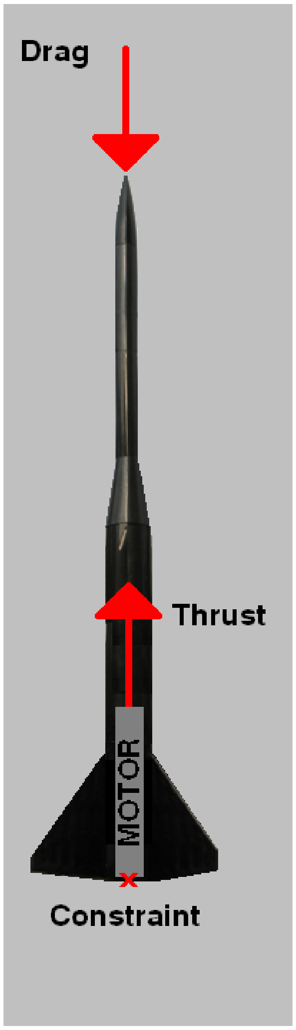

Figure 6: Thrust, Drag, and Constraint Placement

An inertial load was also placed on every component of the body to account for the acceleration. A maximum loading of 6 G's is predicted from initial motor design performance calculations. Therefore a 10 G load was applied to institute a safety factor. An example of the loads and constraints placed on a structural segment is shown in Figure 7.

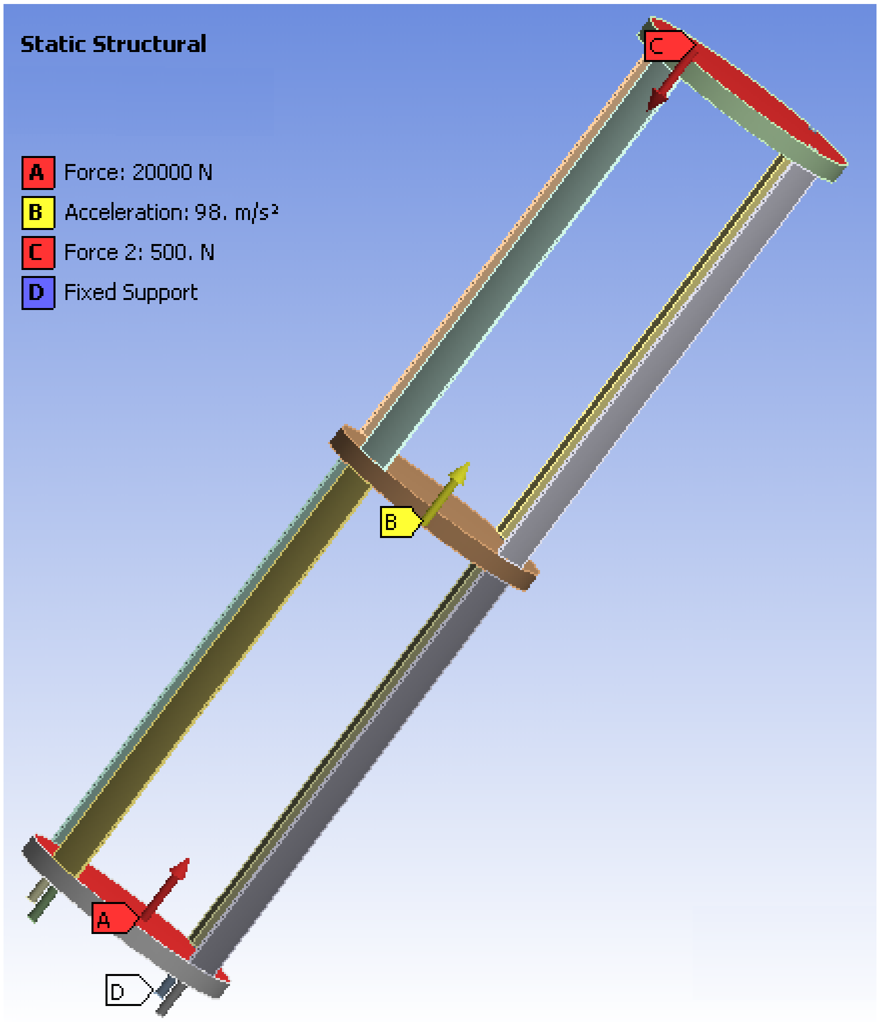

Figure 7: Typical Loads and Constraints Placed on Segment

VI. Static Analysis

The rocket was analyzed using ANSYS Academic Teaching Introductory software. Due to the limitations involving the number of nodes that can be assigned in this software, which utilizes the Finite Element Method, the rocket had to broken up into segments for examination. Refinement also had to be made to the mesh of each segment, Figure 8. This caused the mesh to be less than desirable but still functional. The panels that will compose the skin of the airframe were not included in the analysis since they are not being considered a necessary structural element. However from our prototype it can be noted that they add rigidity to the airframe as a whole.

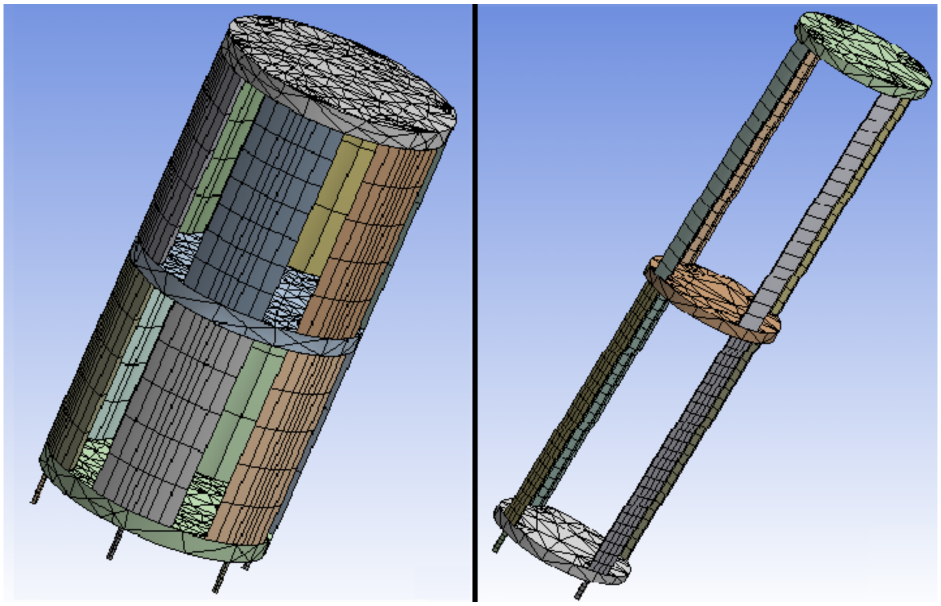

Figure 8: First (Left) and Second Stage (Right) Meshes

After the meshes were generated the loads were placed in the previously discussed locations. A thrust of 20000 N was used since this is close to twice the amount that is predicted from our motor. This allows a safety factor to be established but makes the structure heavier due to the extra support needed to handle the given loading. The total deformation, stress, and strain of the first and second stages are shown in Figure 9 and Figure 10 respectively.

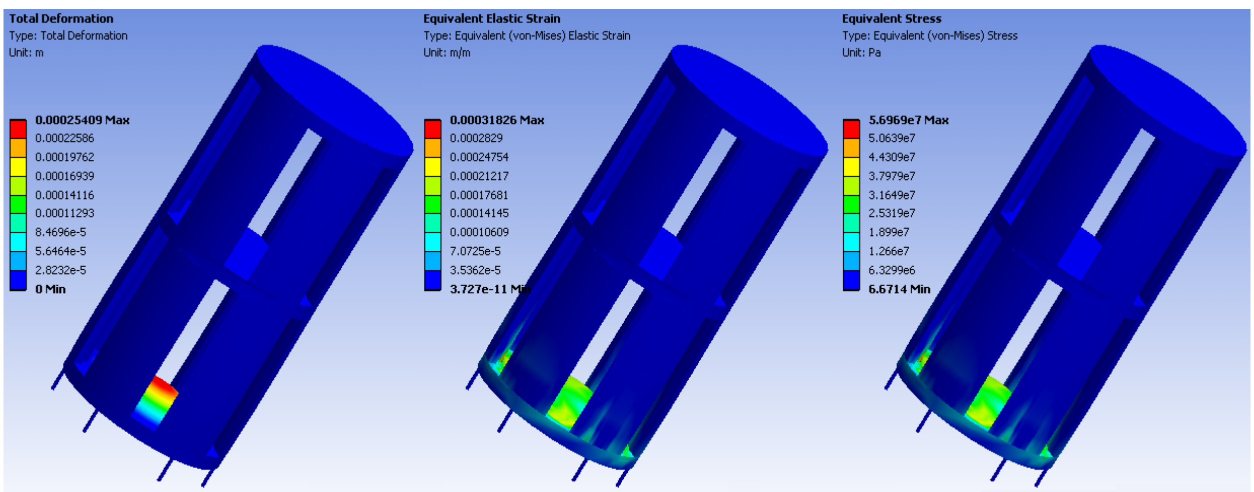

Figure 9: First Stage Deformation, Stress, and Strain

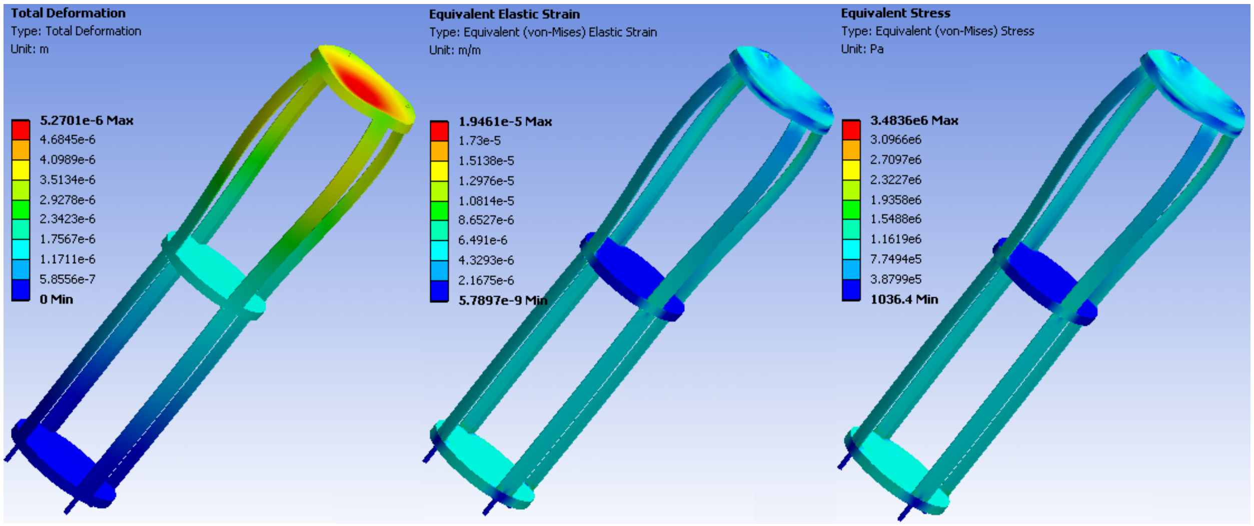

Figure 10: Second Stage Deformation, Stress, and Strain

As anticipated, the structure that composes the first stage can handle the given loading better than the second stage. The maximum stresses on both stages are lower than the yield stresses by several orders of magnitude. This was purposely left this way in order to support the control system that will possibly be installed. The control system will undoubtedly cause more stress on the airframe than displayed in this analysis. Therefore, the structure was not further altered after these results were assembled.

VII. Buckling Analysis

A buckling analysis was performed on the airframe to determine the locations in which buckling could occur and the loads needed to achieve buckling. Results from the first stage and second stage analysis are depicted in Figure 11 and Figure 12 respectively.

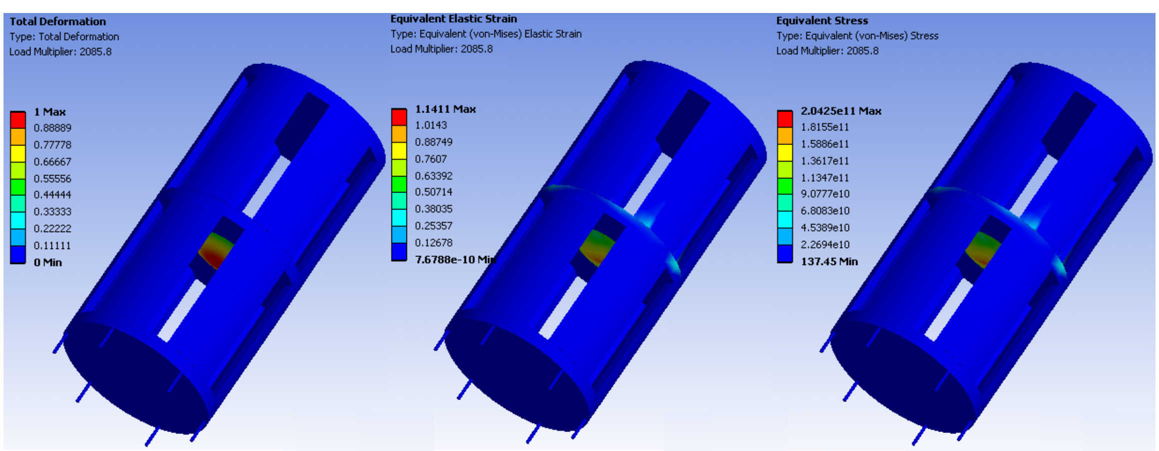

Figure 11: First Stage Buckling Analysis

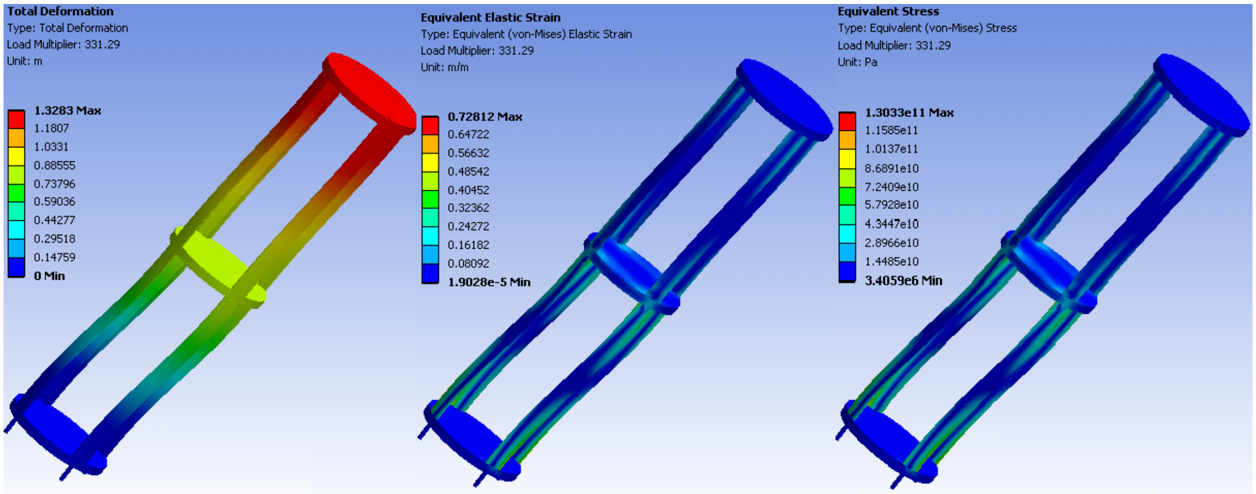

Figure 12: Second Stage Buckling Analysis

Buckling should not occur during the given loading conditions predicted while in flight due to the load multiplier that it takes to cause either stage to buckle.

VIII. Modal Analysis

A modal analysis was also performed to the determine the frequencies and shapes of six vibration modes for the first stage, Figure 13, and the second stage, Figure 14.

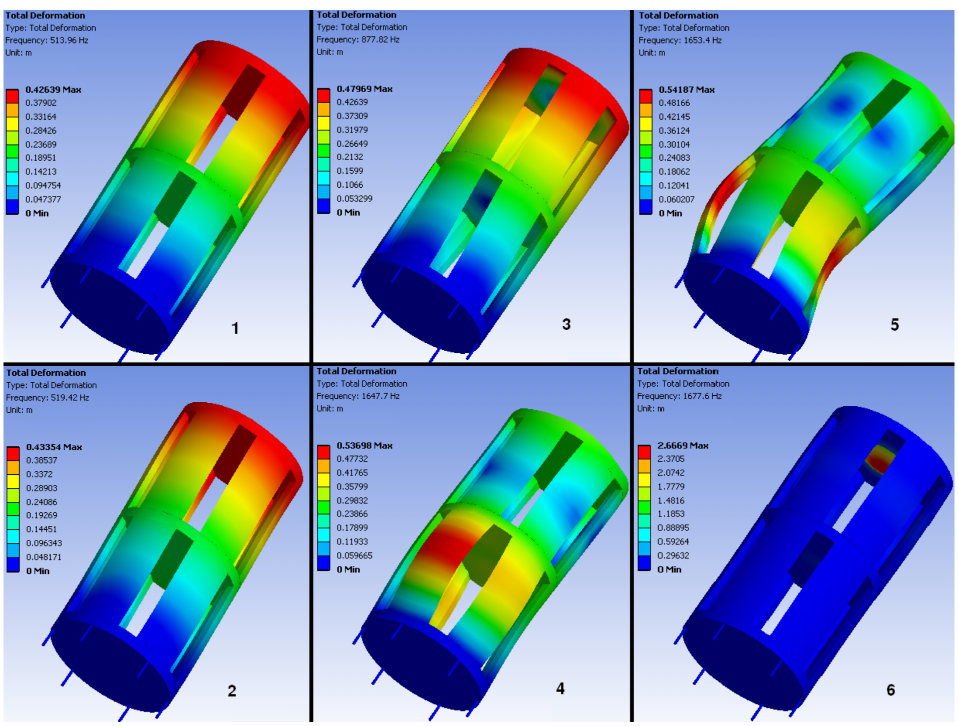

Figure 13: Vibration Modes 1-6 for First Stage

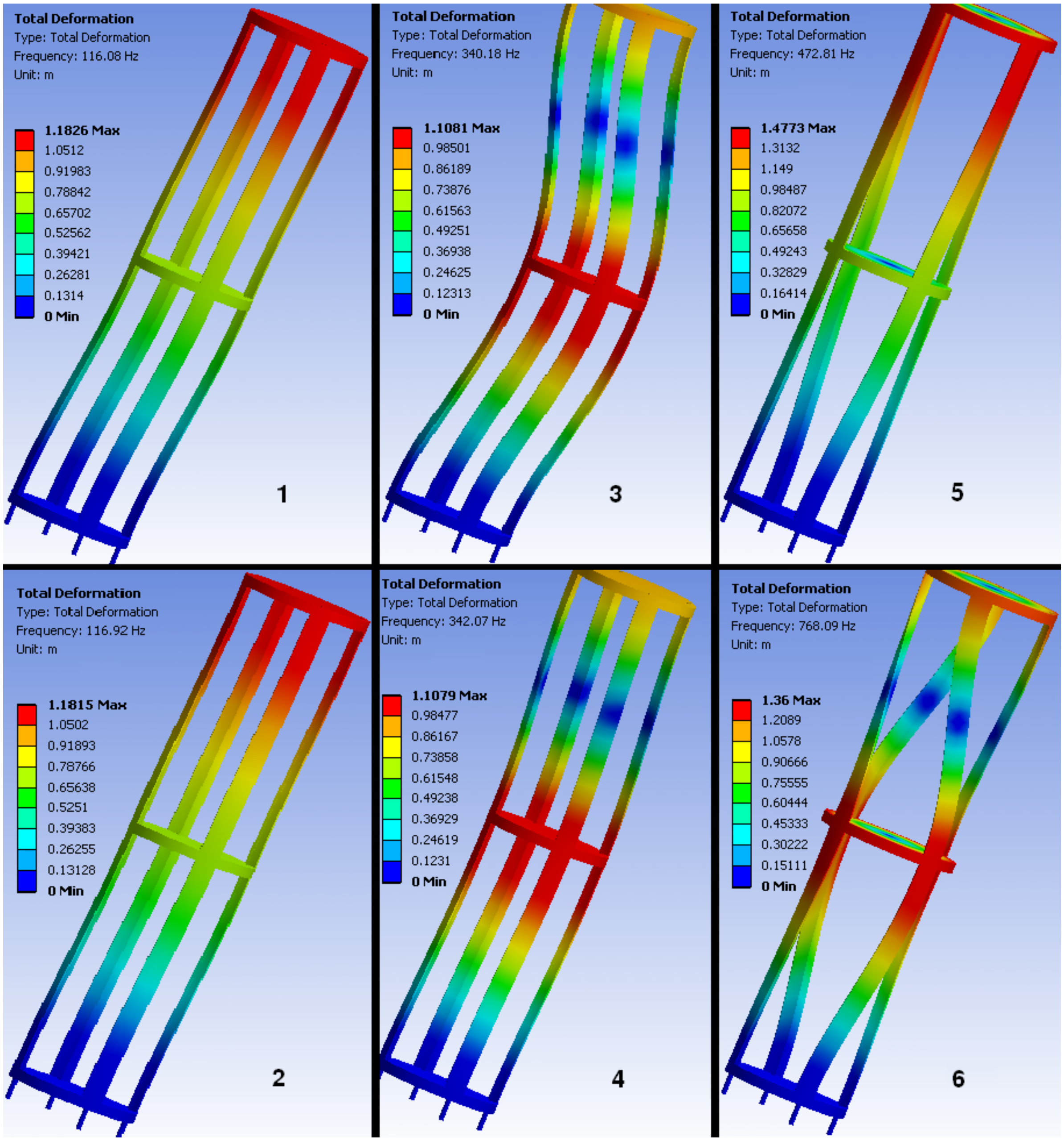

Figure 14: Vibration Modes 1-6 for Second Stage

The transition piece of the rocket will include dampening mechanisms to suppress any vibration that occurs in either stage throughout flight.

IX. Prototype

In order to test our part fabrication and construction techniques, a true scale prototype was made, Figure 15. The only existing modification was an extended first stage that was caused by the inadequate stock of proper tubing needed to simulate the first stage motor. A large tube was inserted in place and not cut due to concerns expressed for a potential reuse on another project. The mass of the prototype was within five percent of the theoretical mass calculated by a CAD program. Static testing will be conducted in the future to test the ANSYS results.

Figure 15: Prototype Pictured with Construction Team

References

[3] Sun, C. T., *Mechanics of Aircraft Structures*, John Wiley & Sons, New York, 2006, pp. 12.

[4] Fleeman, Eugene L., *Tactical Missile Design*, American Institute of Aeronautics and Astronautics, Virginia, 2006, pp. 154.

[5] Chiesa, S., Di Sciuva, M., and Testore, L., "Launch vehicles conceptual design and structural analysis: an integrated approach via FEM," Elsevier Science Ltd., 1999.