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Design of a Test Fixture and Static Load Test for a NACA 0009 Horizontal Stabilizer

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Abstract

Aircraft horizontal stabilizers experience deflection and torsion during flight. The accompanying bending and shear stresses can cause failure if the aircraft is not operated within the correct performance envelope. Analytical models can be created to predict vertical and angular deflection as well as the shear center of the stabilizer. These values can also be found through experimental testing to verify the analytical models that can be used in the future. The proposed senior design project is to create the analytical models for a NACA 0009 horizontal stabilizer from an F1 Rocket of Frazier Aviation and design an experimental structural load test that can be used to verify the analytical models. As part of the experimental structural load test, the team must design a test fixture that will not deflect under the applied load.

Table of Contents

1. Introduction 1
2. Background and Statement of the Problem 7
  2.1 Project Background 7
  2.2 Design Decisions for Text Fixture Creation and Prior Work 8
    2.2 Reusable Test Fixture 10
    2.2.2 Static Load Test 12
    2.2.3 Instrumentation 15
3. Conceptual Designs for the Testing Fixture and Procedure 17
  3.1 Concept #1 17
  3.2 Concept #2 19
  3.3 Concept #3 23
4. Engineering Design Analysis 27
  4.1 Aerodynamic Load Modeling 27
  4.2 Vertical Deflection Modeling 35
  4.3 Shear Center and Angular Deflection Modeling 36
  4.4 Finite Element Deflection Analysis 39
5. Testing and Procedures 41
  5.1 Shear Center Testing 41
  5.2 Vertical and Angular Deflection Testing 42
  5.3 Point Load Testing 46
6. Results 48
7. Lessons Learned 51
8. Conclusion 52
9. References 53
10. Appendix A 54
  10.1 System Hierarchy 54
  10.2 Schedule 55
  10.3 Budget 57
  10.4 Requirements 58
  10.5 Concept of Operations 59
  10.6 Failure Modes and Affects Analysis 60

10.6 FMEA Before December 10th 60
10.6.2 FMEA After December 10th 62
10.7 Mechanical Block Diagram 63
11. Procedure 64
12. Analytical Models MATLAB Code.. 65
Appendix N: ABET Outcome 2, Design Factor Considerations 79

List of Figures

Figure 1: F1 Rocket aircraft with dimensions and location of the horizontal 2
Figure 2: The F1 Rocket aircraft in flight [1]. 3
Figure 3: The horizontal stabilizer of the F1 Rocket aircraft [1]. 3
Figure 4: The important loads and deflections of the horizontal stabilizer. 4
Figure 5: Length and Width of the HS with the elevator controls attached. 5
Figure 6: An example of a static load test on an aircraft wing [2]... 6
Figure 7: Modeling the lift force in a positive-G orientation.. 9
Figure 8: Modeling the lift force in a negative-G orientation.. 10
Figure 9: DarkAero Test Fixture for their aircraft wing [4]. 11
Figure 10: Text fixture that tests one side of the HS and is mounted to the wall [5]. 12
Figure 11: Distributed load created in combination of sandbags and weight plates [4]............... 13
Figure 12: Distributed load modeled with reams of paper [8].. 14
Figure 13: Point loads applied to the HS with hydraulic cylinders [5].. 15
Figure 14: Rulers to measure the deflections created by the lift force [4]................................... 16
Figure 15: Map used to place the strain gauges on the HS with point loads. 17
Figure 16: The first conceptual design.. 18
Figure 17: The second conceptual design. 19
Figure 18: Measuring vertical deflection with rulers.. 20
Figure 19: Plate that will connect to the main portion of the test fixture and the HS.................. 21
Figure 20: The test fixture for Concept #2.. 22
Figure 21: Assembly of the test fixture for Concept #2.. 22
Figure 22: Concept #3.. 23
Figure 23: Steel Table used for testing the HS. 24
Figure 24: Wedges that bolt to the Table-top and the HS to model an angle of attack. 25
Figure 25: The Horizontal Stabilizer without the skin mounted on top of a set of Wedges that are bolted into the tabletop... 25
Figure 26: A NACA 0009 airfoil with nomenclature. 28
Figure 27: An example of a lift force distribution applied to the HS at an angle of attack and position of the aerodynamic center. 28
Figure 28: Free Body Diagram of a horizontal stabilizer. 29
Figure 29: Alternative Free Body Diagram of a horizontal stabilizer with normal and axial forces rather than lift and drag forces pictured. 30
Figure 30: Half of the horizontal stabilizer with 10 elements and defined terms........................ 31
Figure 31: Lift Force calculated for each node for an angle of attack of negative 5 degrees....... 33
Figure 32: Lift Force calculated for each node for an angle of attack of positive 12 degrees...... 34
Figure 33: Vertical deflection of a HS along the length of the HS.. 35
Figure 34: Theoretical Shear Center if the HS from the Trailing Edge....................................... 37
Figure 35: Theoretical angular deflection in degrees for -5-degree angle of attack at 250 Knots. 38
Figure 36: Theoretical angular deflection in degrees for -5-degree angle of attack at 250 Knots. 39

Figure 37: Isometric view of the horizontal stabilizer under a load for a 12-degree angle of attack at 250 knots. 40
Figure 38: Front view of the horizontal stabilizer under a load for a 12-degree angle of attack at 250 knots. 40
Figure 39: Testing for shear center. 42
Figure 40: Loading at the negative 5-degree angle of attack at 350 Knots. 43
Figure 41: Measuring deflection using dial indicators. 44
Figure 42: HS failure during first loading at the 12-degree angle of attack at 250 Knots. 45
Figure 43: Close up of the failed rivet. 45
Figure 44: Picture of the Initial Position of the HS used to measure deflection of the trailing edge using photogrammetry. 47
Figure 45: Picture of the one of the iterations of the HS with the point load added used to measure deflection of the trailing edge with photogrammetry. 48
Figure 46: Comparison of shear center results. 49
Figure 47: Results from loading the HS on the quarter chord with a load representing a -5-degree angle of attack at 250 knots is given below. 51
Figure 48: System Hierarchy. 54
Figure 49: Concept of operations for the chosen concept. 59
Figure 50: Mechanical Block Diagram for the chosen concept. 63

List of Tables

Table 1: Constant values used throughout the MATLAB code. 31
Table 2: Lift Force applied to each element for an angle of attack of negative 5 degrees. 34
Table 3: Lift Force applied to each element for an angle of attack of positive 12 degrees. 34
Table 4: Vertical deflections along the length of the HS for a negative 5-degree angle of attack at 250 Knots. 36
Table 5: Vertical deflections along the length of the HS for a negative 12-degree angle of attack at 250 Knots. 36
Table 6: Results from loading the HS on the shear center with a load representing a -5-degree angle of attack at 250 knots is given below. 49
Table 7: Results from loading the HS on the quarter with a load representing a -5-degree angle of attack at 250 knots is given below. 50
Table 8: The schedule for the senior design project. 55
Table 9: Budget for chosen concept. 57
Table 10: FMEA up to December 10th, part 1. 60
Table 11: FMEA up to December 10th, part 2. 61
Table 12: FMEA after December 10th. 62
Table 13: Design Factors Considered 79

1. Introduction

A horizontal stabilizer controls the pitching, or up and down movement of an aircraft. The horizontal stabilizer (HS) keeps the aircraft flying level and is necessary for flight [1]. It is important to know the deflections and stresses that the horizontal stabilizer will encounter inside of the expected performance envelope of an aircraft. In fact, this helps to determine how to improve future models, but also to ensure that the horizontal is safe during normal operation.

The objective of this senior design project is to create analytical models to predict vertical and angular deflection of the F1 Rocket aircraft horizontal stabilizer for aerodynamic loads like those reported by the National Advisory Committee for Aeronautics (NACA) in Report 759. Also, the team will design and build a reusable test fixture and create and implement a static load test to obtain experimental results corresponding to these loads and to verify the analytical models. The bending stress and shear from bending and torsion can be found using the deflections to determine a total von mises stress that can be compared to the yield strength of the horizontal stabilizer. The schedule and budget being used to properly execute the project in a timely manner can be found in Tables 8 and 9 of Appendix A, respectively. The F1 Rocket aircraft can be seen in Figure 1.

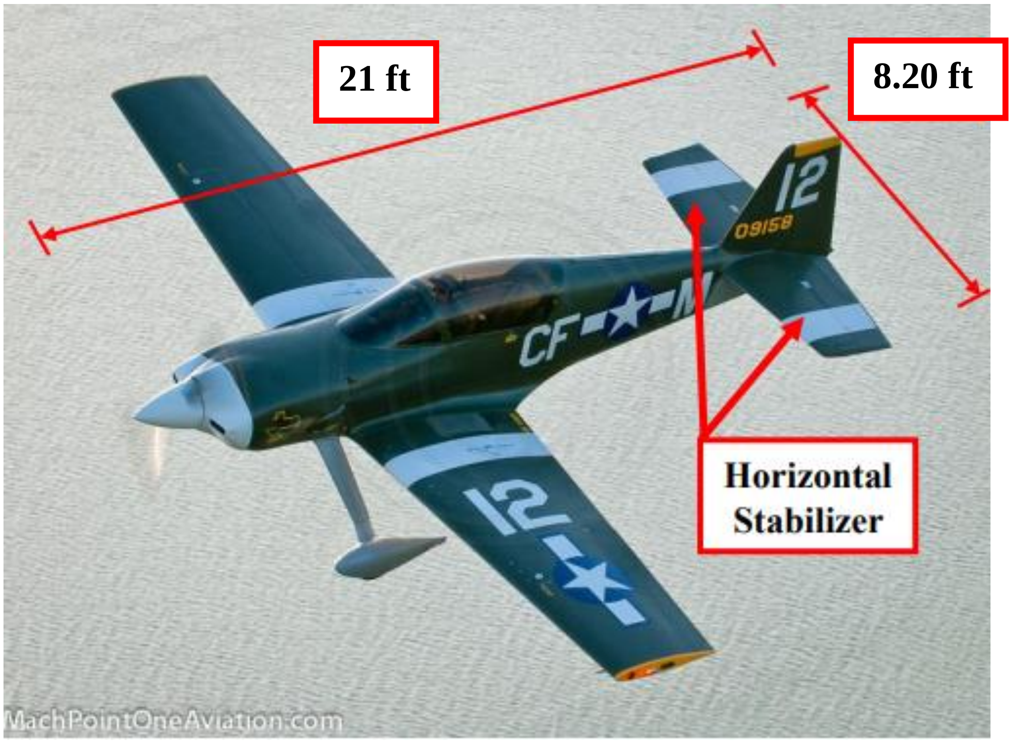

Figure 1: F1 Rocket aircraft with dimensions and location of the horizontal stabilizer [1].

The team worked with Frazier Aviation LLC to perform a static load test on the Mark 1 (Mk 1 or the first design) horizontal stabilizer for the "F1 Rocket" aircraft. Frazier Aviation LLC is a family-owned company that sells affordable, recreational F1 Rocket and F4 Raider aircraft kits for personal use where the aircraft is predominantly built by the customer. This company started in the 1990s and launched their first prototype in November of 2000. By late 2017, over 130 F1 Rocket aircraft have been sold. Frazier Aviation LLC manufactures in-house some of the pieces in the aircraft kit that they sell. The first aircraft built that was partially manufactured by Frazier Aviation was flown in 2000. Up until 2019, there were no major accidents reported concerning the F1 Rocket aircraft [1]. Another view of the F1 Rocket can be seen below in Figure 2.

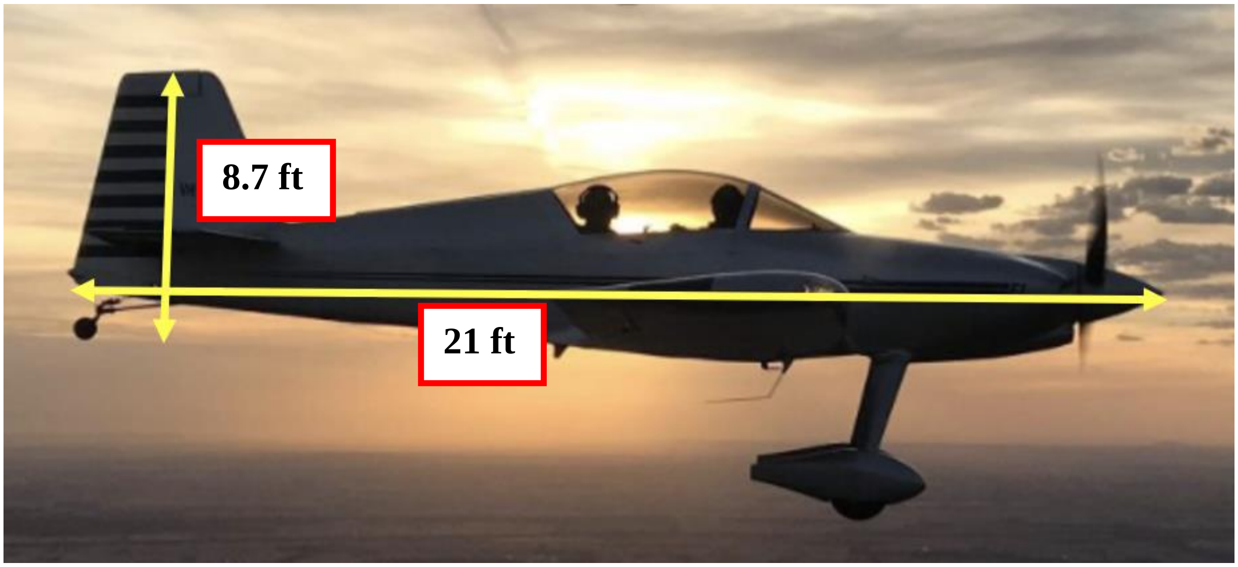

Figure 2: The F1 Rocket aircraft in flight [1].

The F1 Rocket aircraft horizontal stabilizer is shown in Figure 3 and a schematic overview of the important loads and deflections is shown in Figure 4. The horizontal stabilizer experiences vertical and angular deflections in response to the loads as shown in Figure 4. The horizontal stabilizer is mounted to the fuselage, or the main body of the aircraft.

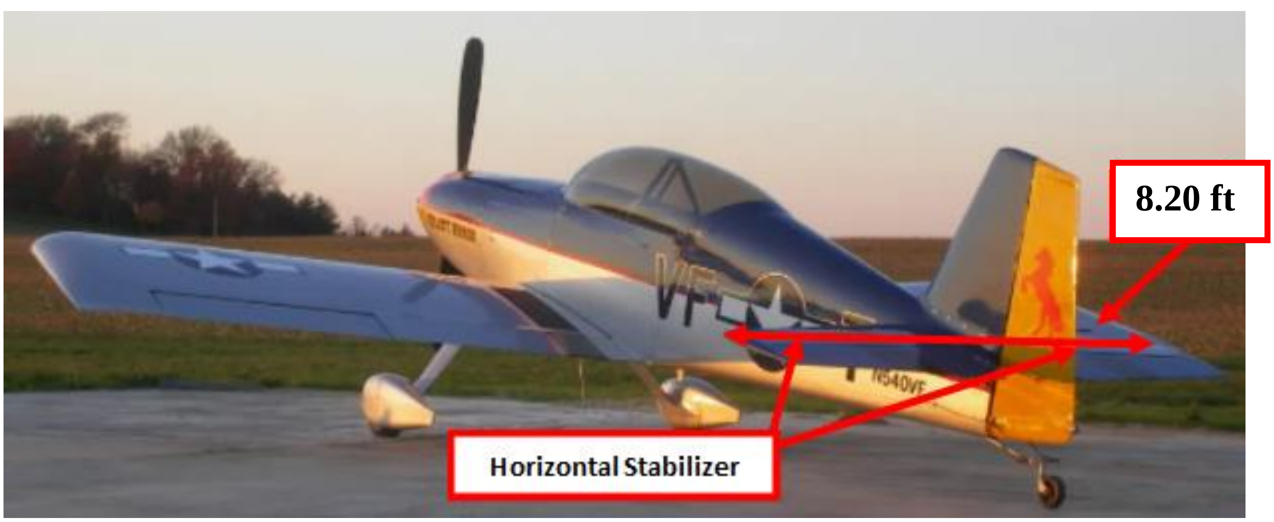

Figure 3: The horizontal stabilizer of the F1 Rocket aircraft [1].

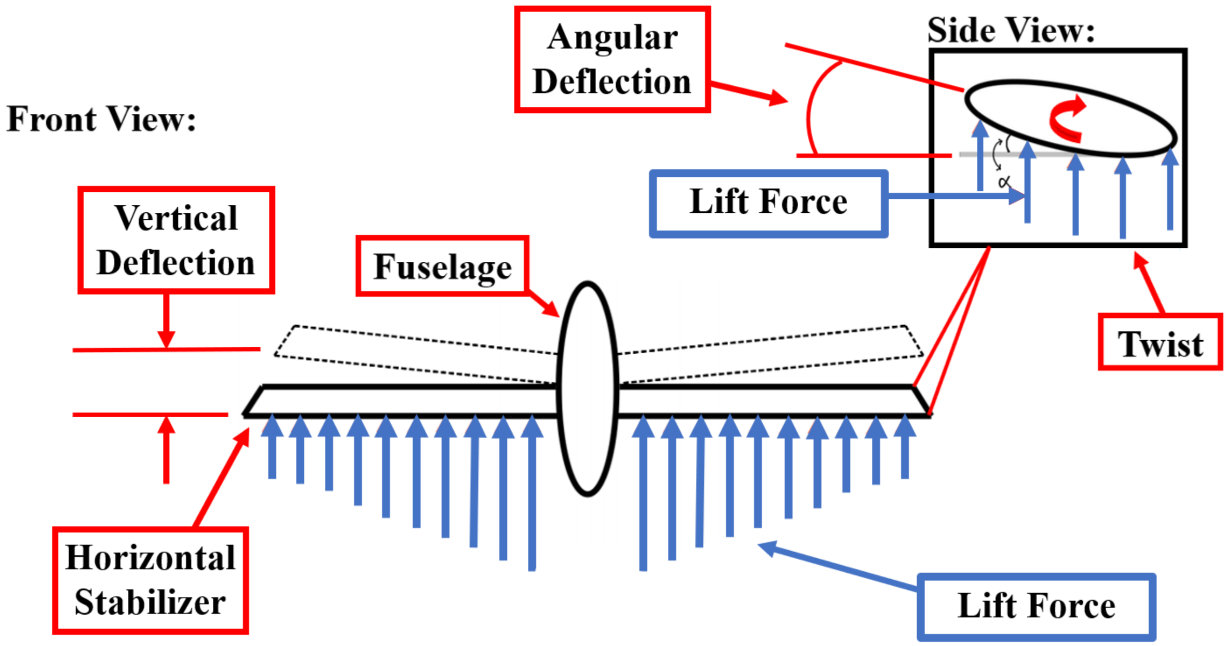

Figure 4: The important loads and deflections of the horizontal stabilizer.

Figure 5 shows a more detailed view of the horizontal stabilizer this project is analyzing, the Mk1 horizontal stabilizer with the elevator control surfaces attached.

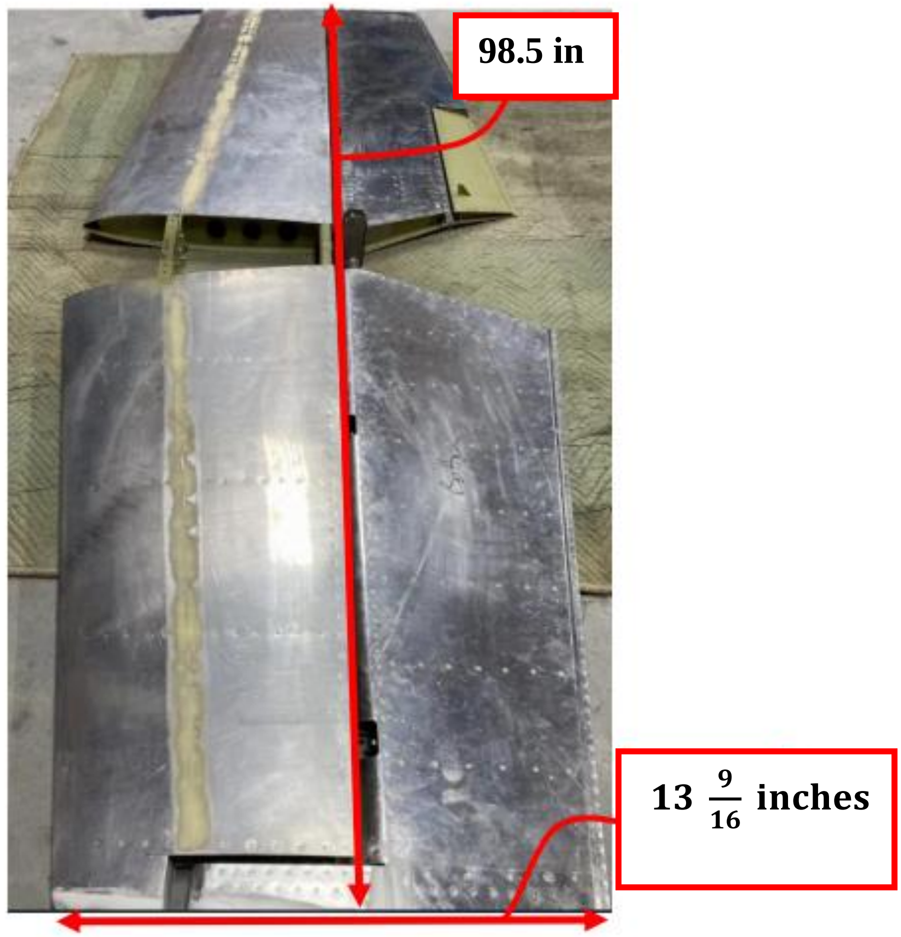

Figure 5: Length and Width of the horizontal stabilizer with the elevator controls attached.

Besides creating analytical models to simulate the aerodynamic loads and predict the deflections pictured in Figure 4, a physical test fixture will be designed, and static load test procedure developed to experimentally gather deflection data under a specified distributed load mimicking the aerodynamic loads the horizontal stabilizer could experience. The static load test fixture and procedure will follow a pattern that has been widely used in the past like that shown in Figure 6.

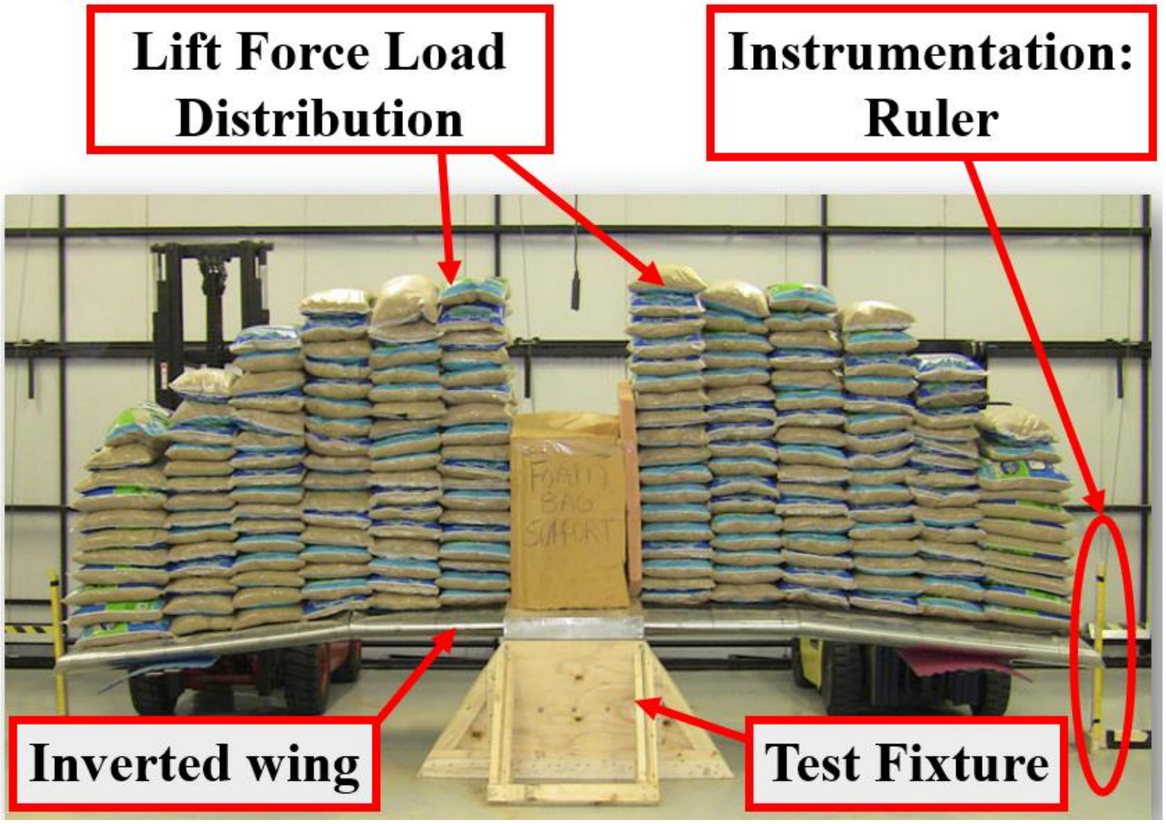

Figure 6: An example of a static load test on an aircraft wing [2].

The deliverables of the project include:

- Analytical models to predict vertical deflection, angular deflection, shear center location, and shear flow
- A reusable test fixture
- A static load test procedure for simulating aerodynamic loads at angles of attack of –5° and 12°.
- To experimentally determine angular and vertical deflections for two specific aerodynamic loads at the edge of the performance envelope and experimentally shear center locations

The remainder of this report gives more extensive project background as well as engineering design analysis that is used to create analytical models to predict deflections which can be used to determine stresses the horizontal stabilizer experiences during flight. Three concepts for creating a static-load test fixture and procedure are shown and the design decisions that were made to reach a final testing concept are discussed. Details of the final chosen concept and analysis showing how well it meets the testing requirements are included as well.

2. Background and Statement of the Problem

2.1 Project Background

The motivation for the project comes from an aviation accident that occurred on December 24th, 2019 [3]. Two appropriately certified pilots took an F1 Rocket aircraft out for an afternoon of "gentlemen's aerobatics" and were able to complete many different maneuvers before the aircraft was damaged during a barrel roll [3]. The N230BW Accident Report discussed that the inspection completed by the Federal Aviation Administration (FAA) revealed that the aircraft was traveling above the maneuver speed limit. It was noted the right horizontal stabilizer disconnected from the fuselage, but the right elevator, left horizontal stabilizer, left elevator, and vertical stabilizer were still attached when the aircraft landed [6]. They were flying an older F1 Rocket aircraft with the Mk 1 empennage.

The horizontal stabilizers for this specific F1 Rocket aircraft have only been tested in flight. This accident has incentivized structural testing of the horizontal stabilizer to assess the load capabilities. The F1 Rocket aircraft is classified as an experimental aircraft by the FAA therefore it must follow the Federal Aviation Regulations: *51% of Major Portion Rule for Experimental Aircraft* [6]. This regulation requires that the customer must build at least 51% of the aircraft and go through an inspection that every experimental aircraft must go through before being registered with the FAA [6]. However, this regulation does not mention the evaluation of the structural capability of the horizontal stabilizer as a requirement. While Frazier Aviation, LLC complies with the major portion requirement, the horizontal stabilizer of the F1 rocket has not been subjected to static load testing. The FAA does not require structural testing of experimental aircraft to determine if it is safe for flight, therefore, a structural assessment verifying the safety of the horizontal stabilizer under typical load conditions inside the performance envelope will help the reputation of Frazier Aviation LLC as well as help improve future horizontal stabilizer designs and provide the initial data for more advanced aircraft analysis.

The analytical models for deflection and the experimental tests need to have aerodynamic loads specified that will be applied to the horizontal stabilizer. Report 759 from NACA contains information about the NACA 0009 airfoil, a thin symmetric airfoil which is used on the Mk-1 stabilizer. NACA is federal agency that was founded on March 3, 1915, to undertake and promote aeronautical research [7]. This information was used as well as thin-airfoil theory to predict aerodynamic loads for speeds ranging between 120 mph and 280 mph and an angle of attack ranging from -5 to +12 degrees. How the shape of the distributed load representing the aerodynamic loads were determined, as well as the predicted vertical and angular deflections as shown in Figure 4, will be discussed in more detail in the engineering design analysis. From the predicted vertical and angular deflection bending stresses and stresses from twist can be determined.

With the shape of the load distribution from the aerodynamic load analysis determined together with a test fixture the proper masses can be loaded onto the stabilizer and vertical and angular deflections can be measured. The experimental data can be used to verify and refine the analytical models, with the goal that the analytical model predictions are less than 10% error relative to the experimental data. With an accurate analytical model, future analysis can be run on the HS without performing the experimental tests. The team will provide the experimental data and models to an aerospace structural engineer for future use in determining the safety of the HS and examining flutter phenomena.

For this senior design project, the team will be completing an analysis on vertical and angular deflection and exclude an analysis on the flutter phenomenon. The team will not be determining if the horizontal stabilizer is safe for flight or if a redesign is necessary; an aerospace engineer will decide if the analytical models are accurate or not then determine the safety of the horizontal stabilizer. The creation of the analytical models is discussed in the engineering design analysis.

2.2 Design Decisions for Text Fixture Creation and Prior Work

The preliminary design decisions the group needed to make before coming up with detailed design concepts are discussed in this section. The loads on the horizontal stabilizer can potentially be decomposed into two orthogonal loads in the normal and axial directions, however, the team decided to apply the loads to the horizontal stabilizer which would be fixed at the intended angle of attack to avoid having to load in two directions. Another design decision that was made was to model the horizontal stabilizer upside down using a negative-G test orientation. The negative-G orientation is where the horizontal stabilizer is flipped upside down so the lift force is applied to the top of the structure instead of the bottom. Since the lift force is applied to the top, we can apply the force directly on the bottom plate. An example of positive-G orientation is shown below in Figure 7 and the negative-G orientation in Figure 8 where it is essentially the positive orientation flipped upside down.

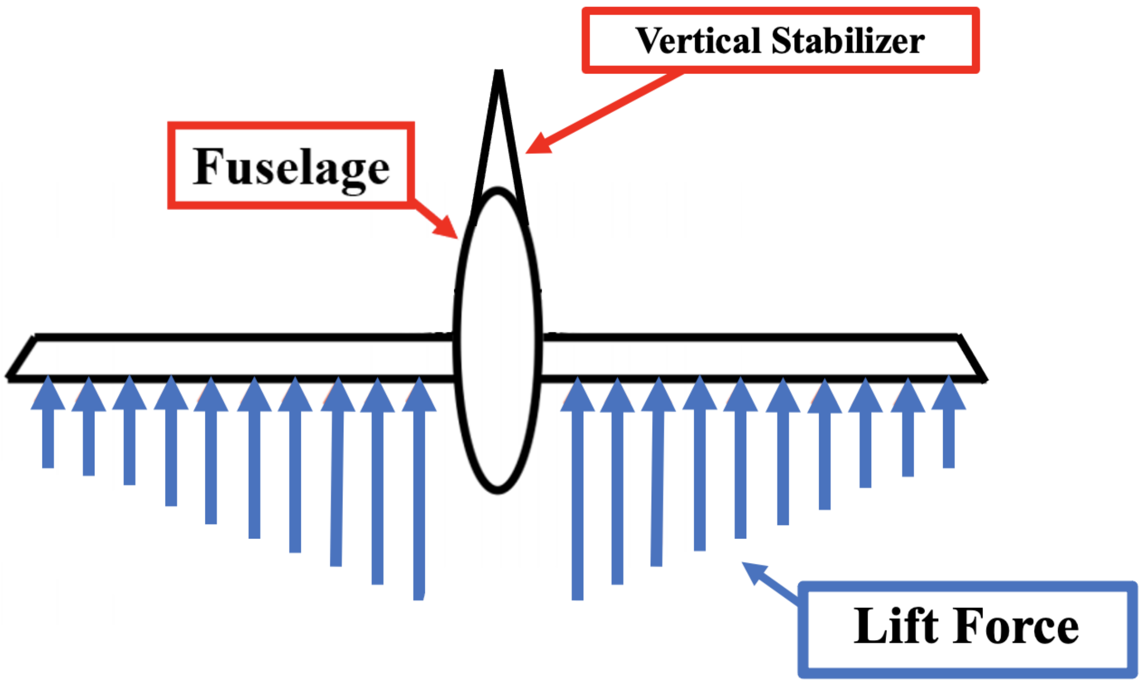

Figure 7: Modeling the lift force in a positive-G orientation.

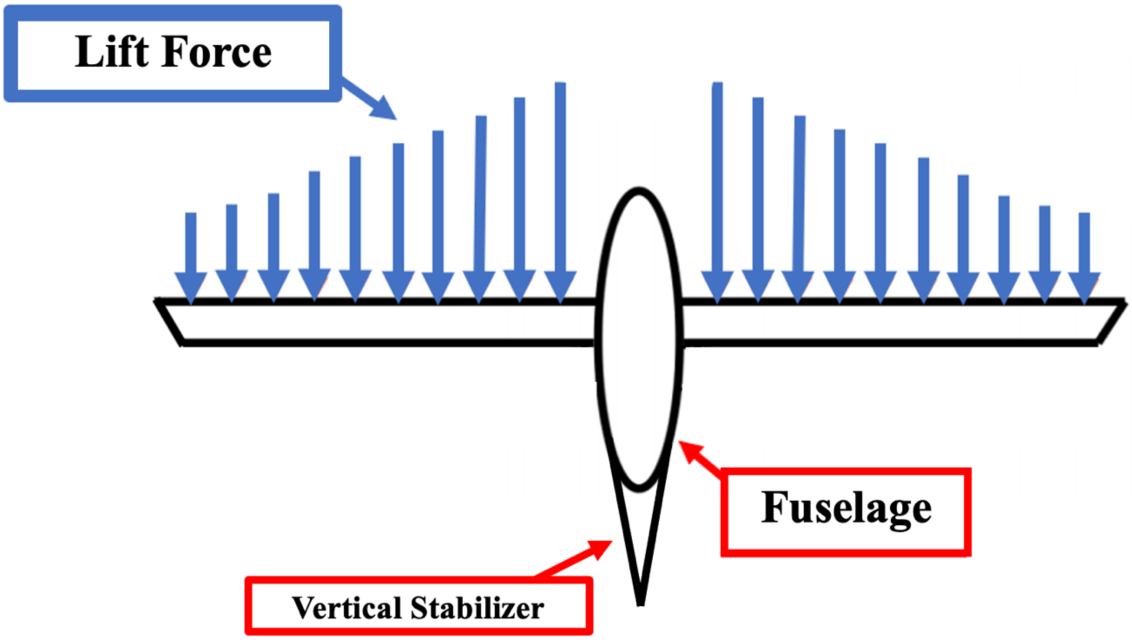

Figure 8: Modeling the lift force in a negative-G orientation.

2.2 Reusable Test Fixture

One of the first design decisions the group encountered was determining how to build a reusable test fixture to be able to perform the static load test. The test fixture needs to be reusable, meaning Frazier Aviation LLC can use it in the future to test new models of the F1 Rocket aircraft and it will not corrode over time. Researching previous static load testing methods showed that commonly the lift force is applied in the negative-G static load test configuration with the horizontal stabilizer upside down.

One of these previous methods is from a group of engineers who created a page on YouTube to publish their project as they design and build an aircraft, the DarkAero. In their YouTube video, “CARBON FIBER WING – Proof Load Test Setup! (Wing Load Test)”, the team structurally tested their carbon fiber aircraft wing [4]. The group designed a test fixture to support both wings at the same time as shown in Figure 9. When designing the test fixture, the team decided to go with a predominantly wooden structure to save money but reinforce it with steel rods in some locations [4]. DarkAero Inc designed their test fixture to use the entire horizontal stabilizer rather than half of it and there were no reported issues with their test fixture.

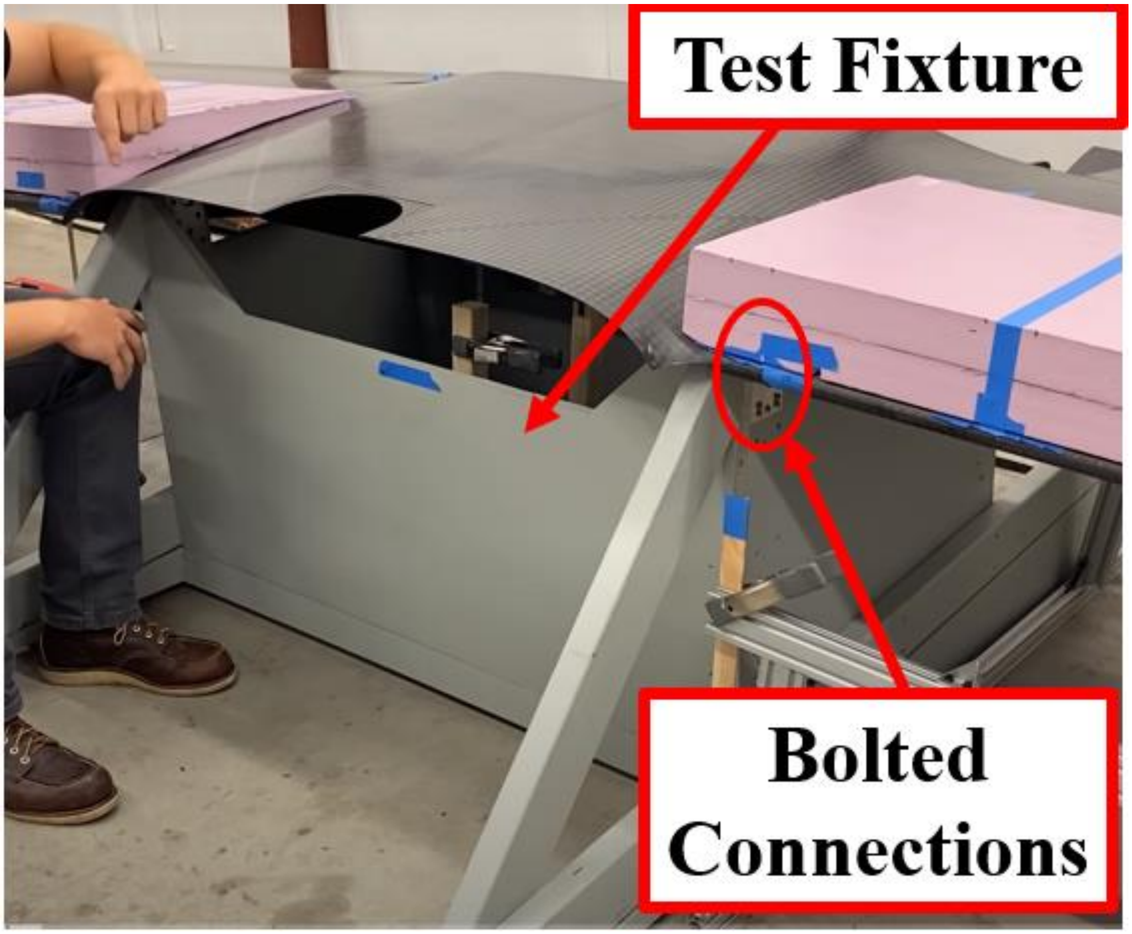

Figure 9: DarkAero Test Fixture for their aircraft wing [4].

In the research article, *Numerical and Experimental Investigation on the Structural Behavior of a Horizontal Stabilizer under Critical Aerodynamic Loading Conditions*, the engineers performed a structural load test on a horizontal stabilizer and designed a realistic test fixture to complete the analysis [5]. The test fixture is shown in Figure 10 and only tests half of the horizontal stabilizer instead of modeling both sides. They designed an upper and lower plate that matched the curvature of the horizontal stabilizer where it attaches to the aircraft. Next, they attached the plates to two C-beams that would compress the horizontal stabilizer together between the two plates creating a realistic connection between the horizontal stabilizer and fuselage. The plates are there to "enforce a continuity constraint" [5]. The test fixture is mounted to a wall through bolted connections as shown in Figure 10. One of the advantages of this test fixture is that the customized plates mimic how the horizontal stabilizer is mounted to the fuselage. They were trying to ensure the horizontal stabilizer was going to perform the same way during the experimental test as it would when fully integrated with the airplane. The report did not mention any complications during the analysis. It also did not mention any analysis completed to ensure the structure the text fixture was mounted to would not fail.

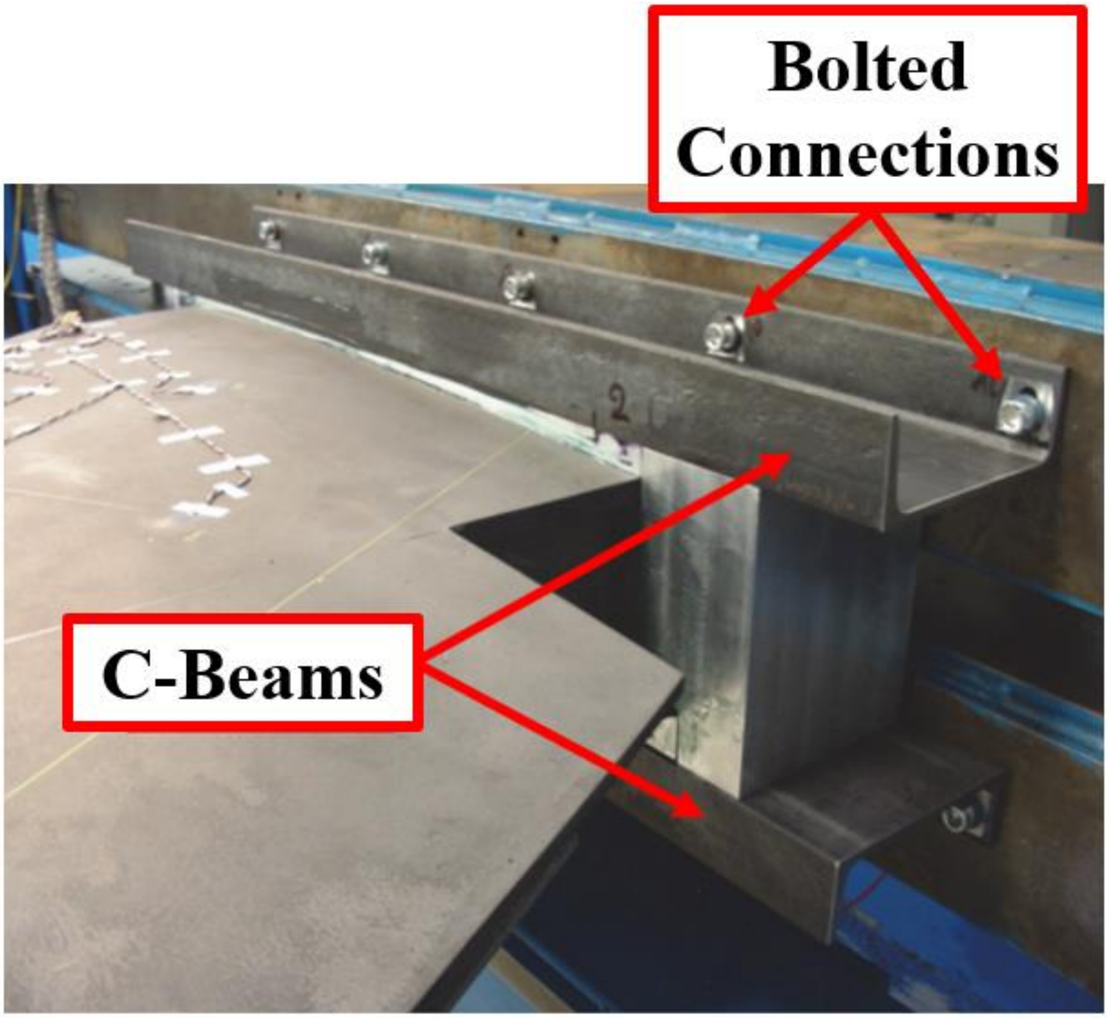

Figure 10: Text fixture that tests one side of the horizontal stabilizer and is mounted to the wall [5].

2.2.2 Static Load Test

Another design decision the team had to make was determining how to apply the distributed lift force onto the horizontal stabilizer. DarkAero, Inc loaded their aircraft wing with sandbags to represent the distributed load as shown in Figure 11 [4]. They also added foam to the wing to help evenly distribute the force over the airfoil. They used jack stands to hold the wing in a resting position, loaded the wing, and then released the jack stands [4]. The foam provided an advantage because not only does it allow the lift force to be evenly distributed along the surface of the horizontal stabilizer, but it also prevented the sandbags from sliding off the wing. The jack stands provided an easy way to ensure the wing would not fall very far if failure occurred as a safety measure.

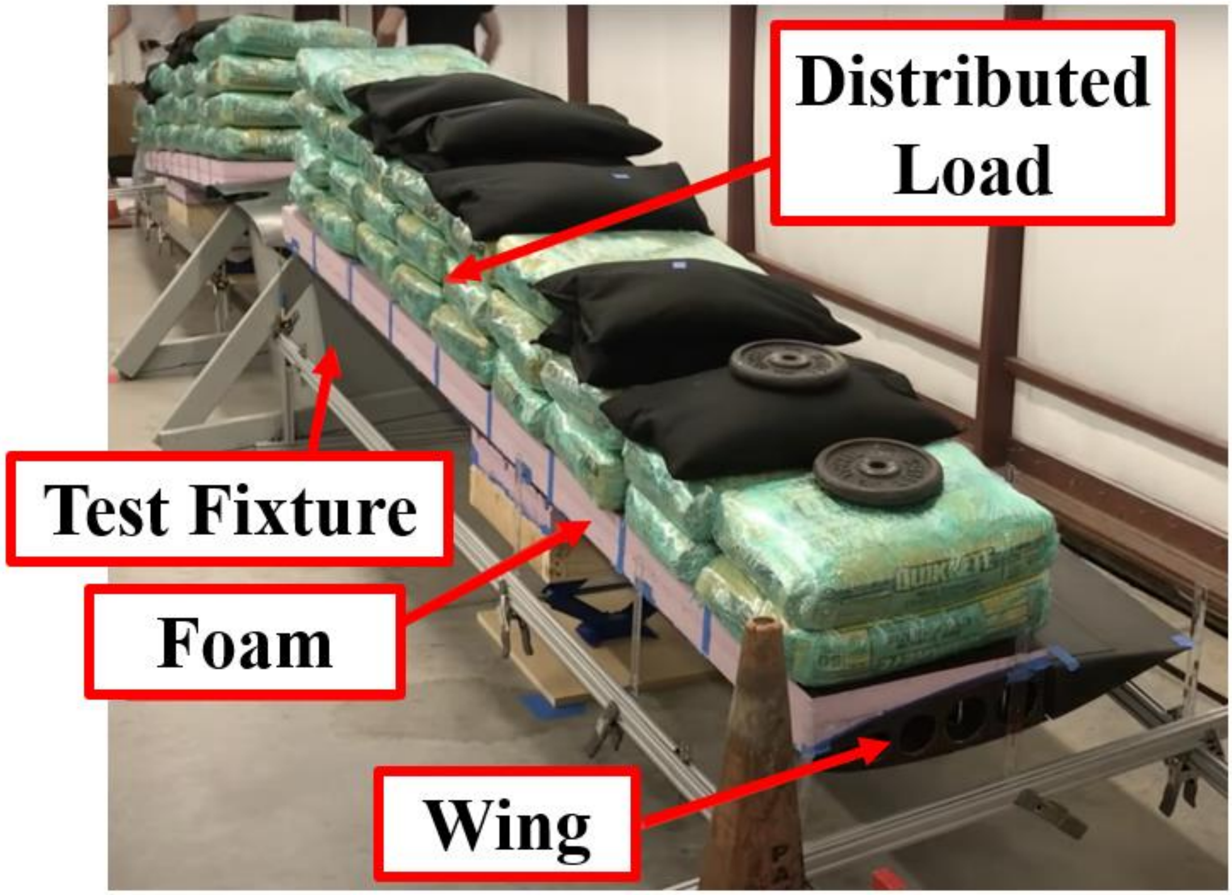

Figure 11: Distributed load created in combination of sandbags and weight plates [4].

Stephen Haley, author of *Design Optimization and Verification of a Horizontal Stabilizer for the SeaStryder600 Wing-In-Ground-Effect (WIG) Aircraft*, structurally tested a mock horizontal stabilizer by loading it with reams of paper and used a checkered grid for backdrop behind it to measure the deflection by capturing high-quality images at 60 frames per second [8]. Figure 12 shows the checkerboard background and the horizontal stabilizer loaded with reams of paper to represent the distributed lift force. This provided a simple way to measure deflection successfully with no reported issues for this portion of the experiment. Reams of paper are relatively inexpensive, and this is a simple way to add smaller loads to the horizontal stabilizer. Haley did not report actual deflections because the test was not for an actual horizontal stabilizer but instead a cantilever beam to prove the text fixture concept.

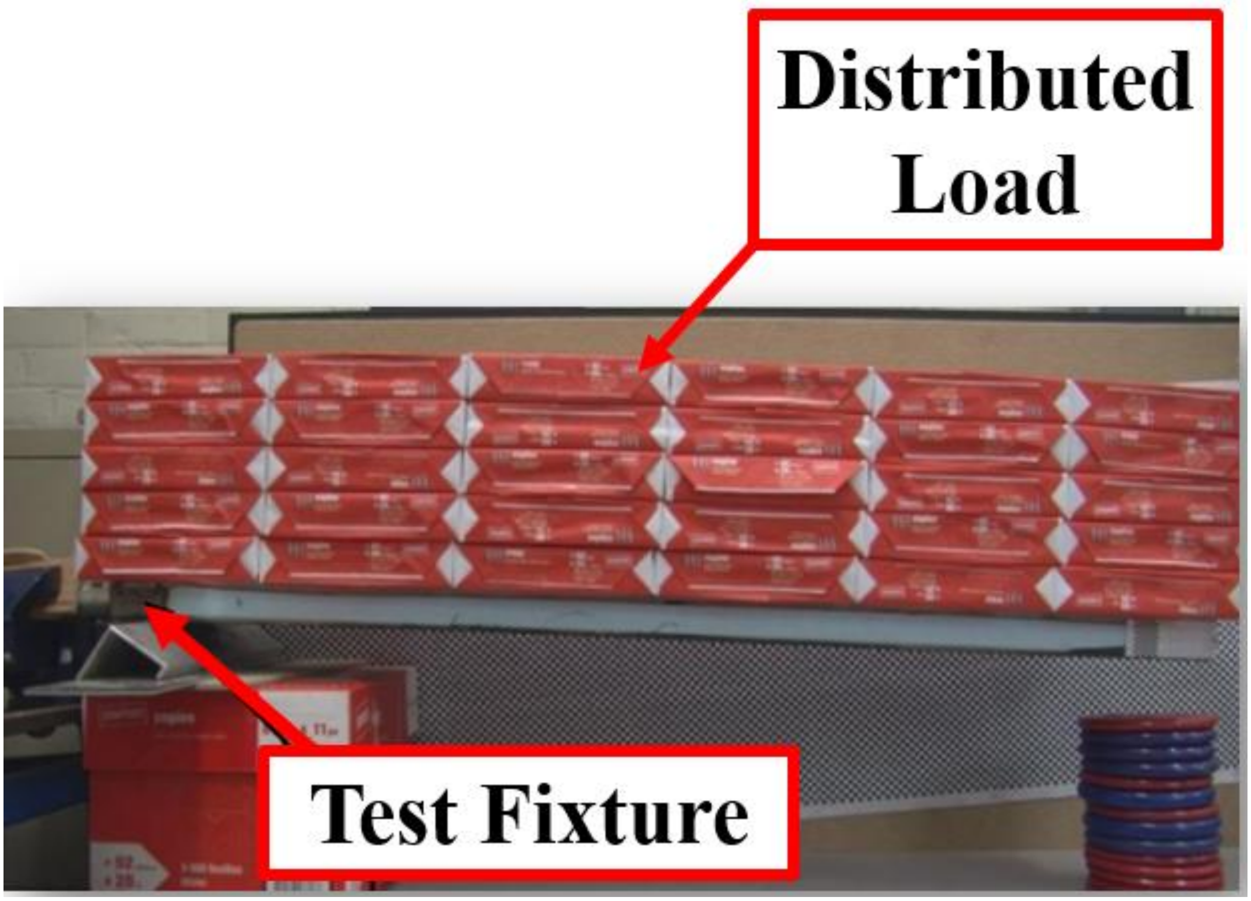

Figure 12: Distributed load modeled with reams of paper [8].

Instead of using a distributed load to model the lift force, the engineers who wrote, *Numerical and Experimental Investigation on the Structural Behavior of a Horizontal Stabilizer under Critical Aerodynamic Loading Conditions,* used point loads. Point loads were applied to the end of the horizontal stabilizer with hydraulic cylinders as shown in Figure 13 [5]. Their team had to use Finite Element analysis to determine how the distributed load would translate as a point load [5]. They were looking for strain of their horizontal stabilizer and through their analysis, it was found that the experimental strains obtained were in good agreement with the numerical outcomes since there was less than an 8.5% relative difference [5]. Using point loads is a design decision that the team considered, though a distributed load was decided upon to try to mimic the aerodynamic loads more accurately.

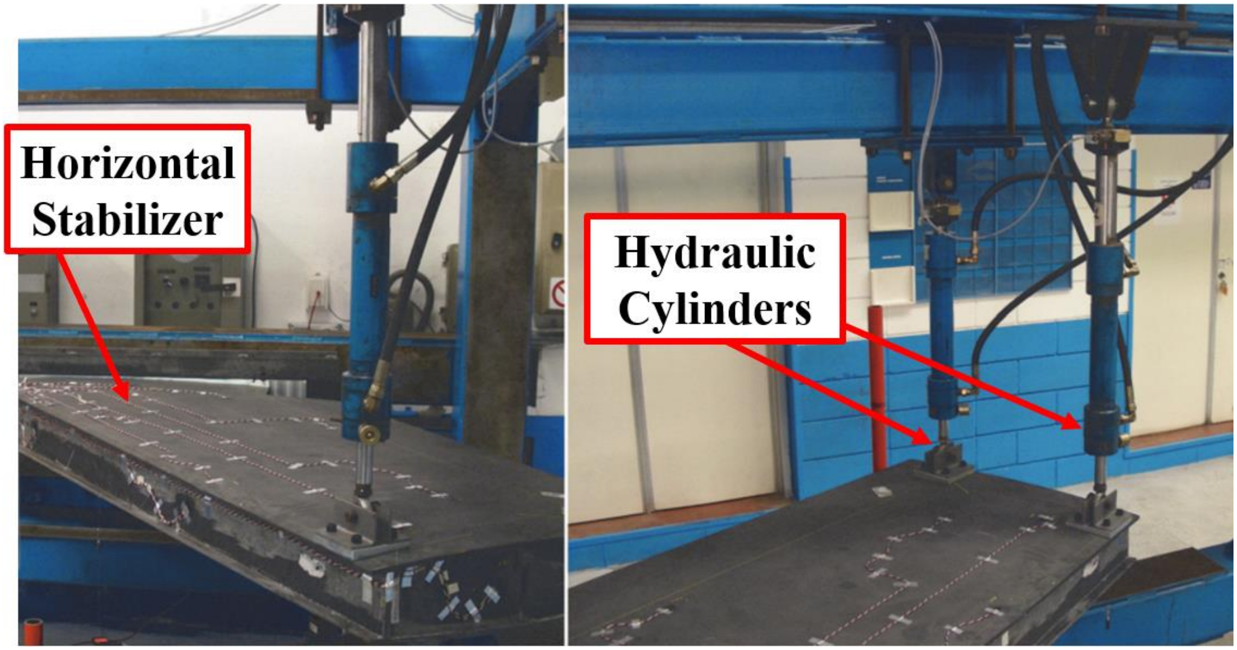

Figure 13: Point loads applied to the horizontal stabilizer with hydraulic cylinders [5].

2.2.3 Instrumentation

Lastly, the team needed to determine how to instrument the horizontal stabilizer to obtain accurate data. DarkAero Inc. set up many rulers set up around the wing profile perpendicular to the ground to measure the initial height of the wing at different locations. Cameras were set up to capture vertical and angular deflection of the wing measured by the rulers throughout the experiment. Once the support from the jack stands has been removed, the photos can be used to determine the initial and final height of the wing and therefore experimentally solving for the vertical and angular deflection [4]. Figure 14 shows an example of the rulers set up to capture angular and vertical deflection. There are a few advantages to using rulers to measure deflection. One being they are inexpensive and the other being this mechanism is not complicated and it would be easy to determine the deflection by reading off the rulers. A disadvantage would be that the rulers may have limited accuracy.

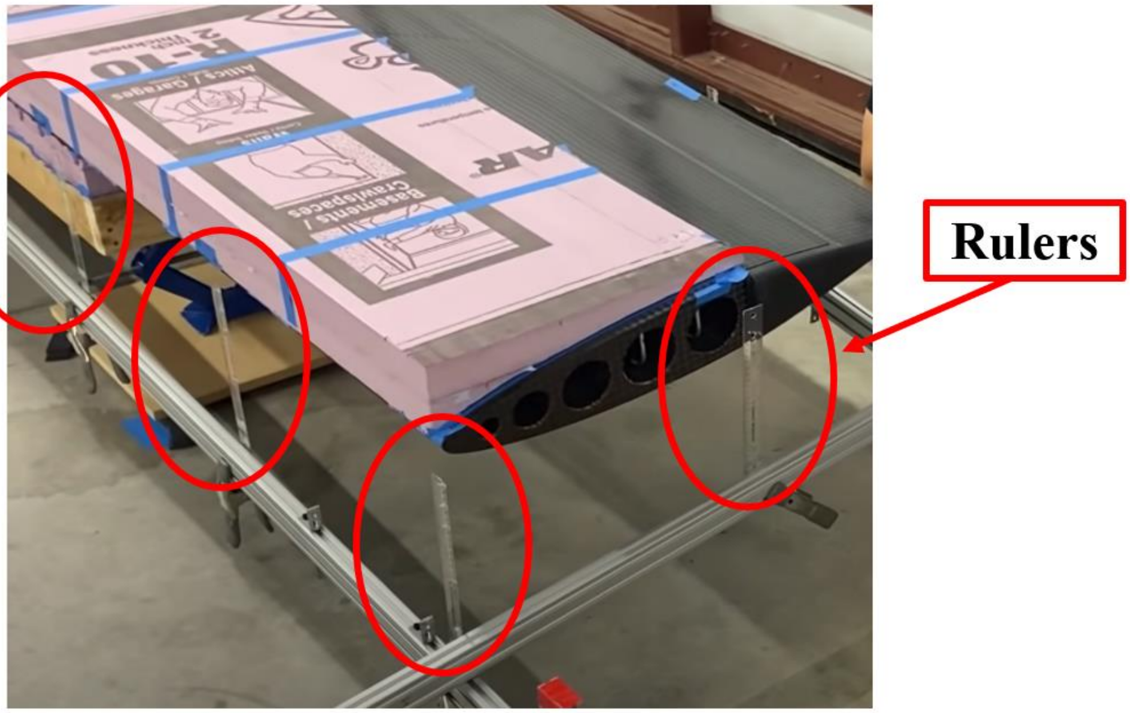

Figure 14: Rulers to measure the deflections created by the lift force [4].

In *Prediction and Measurement of Loading Stress on the Beechcraft King Air Tail Section* by Trung- Duoung H. Nguyen, a tail section of the Beech 200 was tested to find the shear center with strain gauges [9]. The team considered using strain gauges to instrument their horizontal stabilizer and this research article gave some good insight on with the strengths and limits of strain gauges. The researcher used a specific strain gauge that is capable of measuring strain in three directions and can be used to measure torsional deflection. A noted issue was that the adhesive used to hold the strain gauges onto the horizontal stabilizer only held on for a short amount of time [9]. The strain gauges had been rendered unusable due to incorrectly applying the strain gauges, the usage of subpar adhesive, and/or prior stretching of the gauges [9]. While these type of strain gauges can provide translational and angular strains, there were many complications that the engineer encountered while using the strain gauges.

The engineers measuring the deflection of their horizontal stabilizer in *Numerical and Experimental Investigation on the Structural Behavior of a Horizontal Stabilizer under Critical Aerodynamic Loading Conditions*, used strain gauges to instrument their horizontal stabilizer [5]. Figure 15 is the map they used to set up the strain gauges. As mentioned before when discussing loading types, this method yielded accurate results, but the placement of the strain gauges on the horizontal stabilizer was determined in a straightforward way corresponding to the point loads [5]. If a distributed load were used, it would sit on top of the strain gauges and the strain gauges may not read accurate results and the determination of the placement of the strain gauges may not be as straightforward.

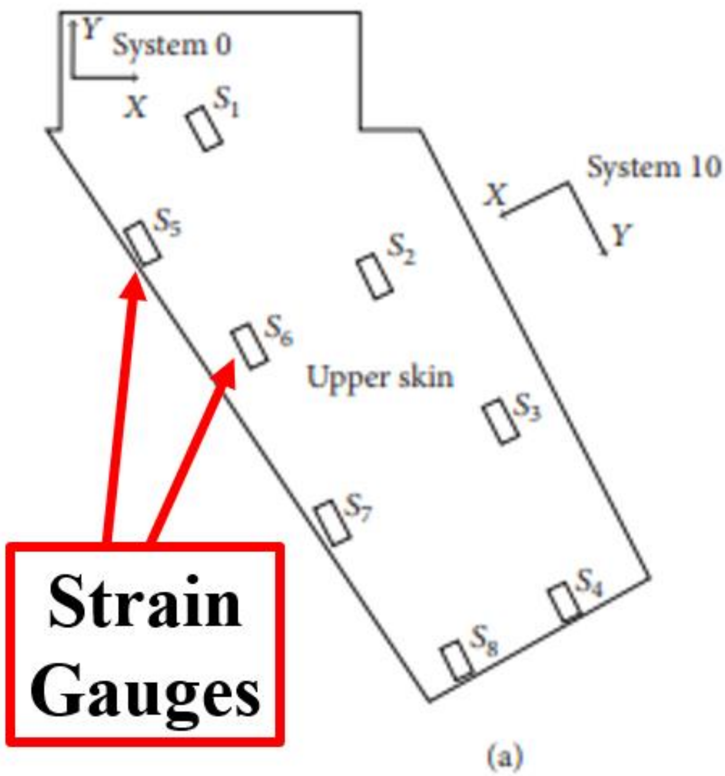

Figure 15: Map used to place the strain gauges on the HS with point loads.

3. Conceptual Designs for the Testing Fixture and Procedure

3.1 Concept #1

The first conceptual design the team came up with for the testing fixture and static load procedure has a test fixture that mounts the horizontal stabilizer to the wall and the angle of attack can be changed through bolted connections. A distributed load corresponding to the lift force will be applied to the horizontal stabilizer in a negative-G orientation. The distributed load will physically be applied using a combination of cement bags, sandbags, and weight plates.

Cement bags can be purchased at different weights. Strain gauges will be used to measure stresses and deflections and will be located where the sandbags are not, so the strain gauges will function properly. The strain gauges will record data to a computer software that the team can later analyze. A layer of foam will be added to the surface of the horizontal stabilizer to make a parallel surface the ground so weight can be added to exact locations along chord line. The foam will also help the weight to not slide off the horizontal stabilizer due to its curvature. A jack stand will be used to counter any deflection that the horizontal stabilizer might see before the entire load is added. Once the load is added to the specific angle of attack, the jack stands will be lowered, and the strain gauge will measure the stresses. The first conceptual design is shown in Figure 16 below.

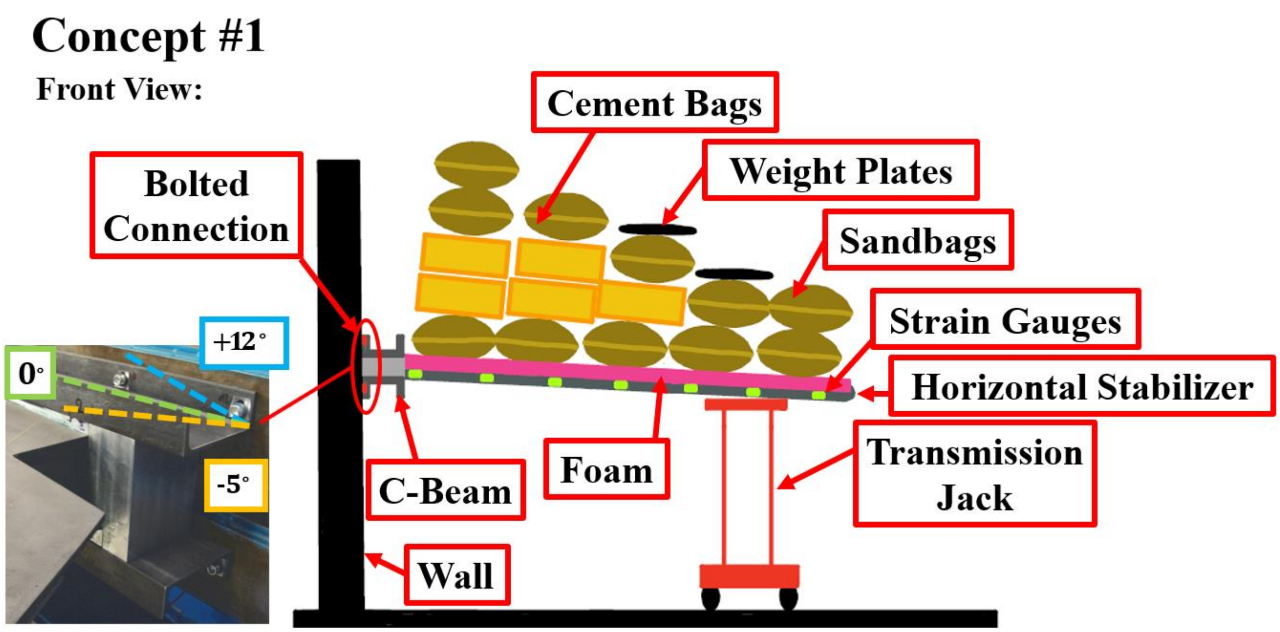

Figure 16: The first conceptual design.

The advantage of this design is that the test fixture only uses half of the horizontal stabilizer so if it breaks or plastically deforms, we will be able to use the other half to finish testing. We will also only need half of the weight compared to testing with the entire horizontal stabilizer. Also, if calibrated correctly, the strain gauges can give very accurate data, but the team is not familiar with setting up and operating the strain gauges. The expected deflections are large enough to be measured using other methods such as dial indicators. Lastly, it would be difficult to ensure that the wall would not collapse when the horizontal stabilizer and the distributed load are applied.

3.2 Concept #2

The second concept the team designed is the most creative design because instead of using a solid weight such as a sandbag, water will be used to apply the lift force. This design uses a two-sided test fixture for the entire horizontal stabilizer in a negative-G orientation. The instrumentation of the horizontal stabilizer to measure deflection is rulers. Rulers will be set up around the horizontal stabilizer to measure the vertical and angular deflection of the structure as the load is added. Jack stands will be used to support the horizontal stabilizer. The second concept is shown in Figure 17.

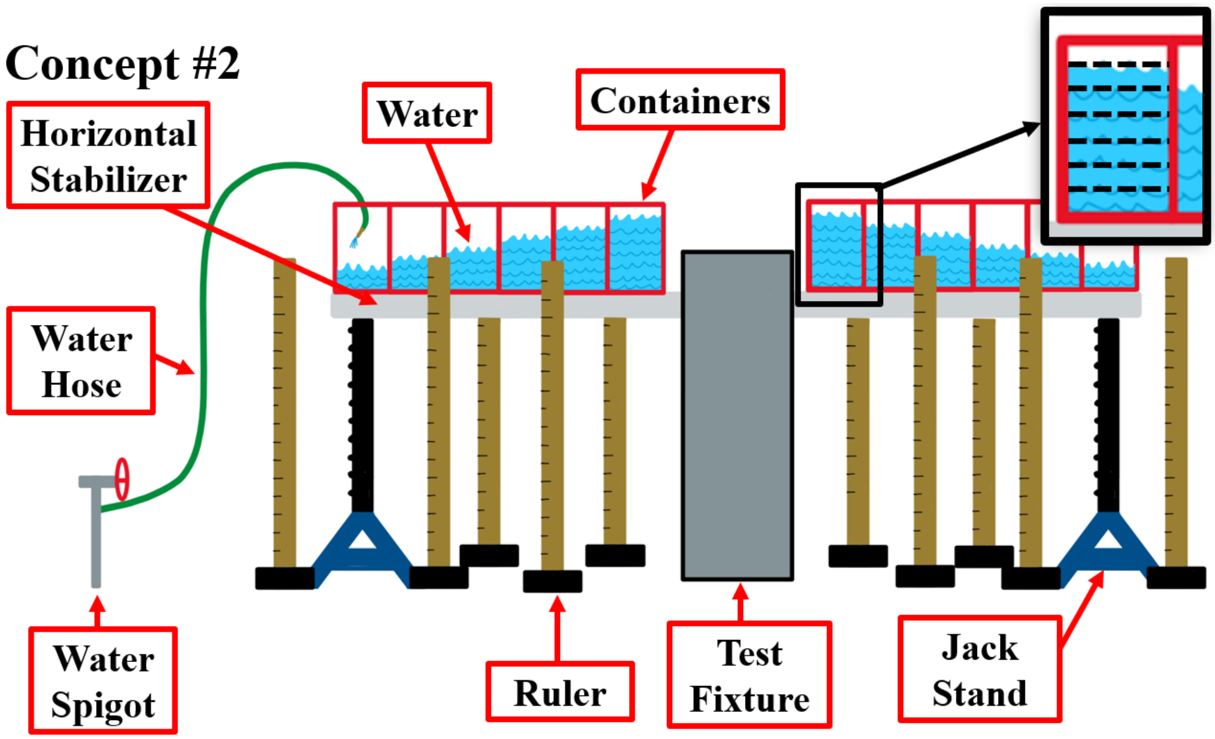

Figure 17: The second conceptual design.

The rulers will be set up around the horizontal stabilizer as shown in Figure 17, but Figure 18 gives a clear example of how rulers will be used to measure the deflection of the beam.

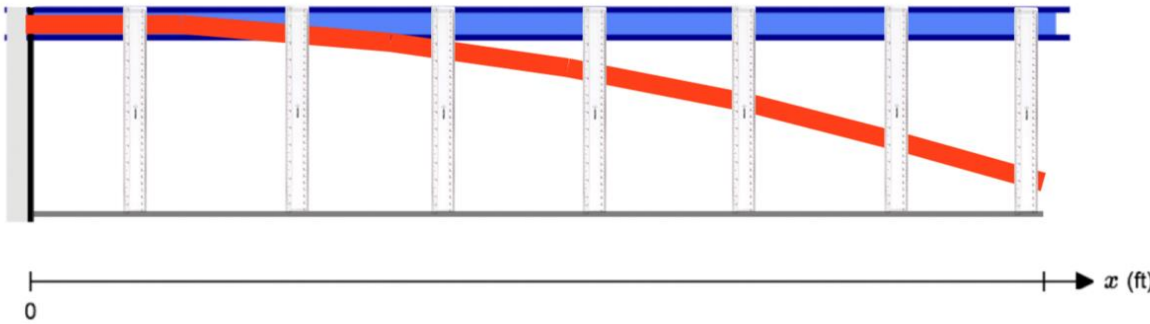

Figure 18: Measuring vertical deflection with rulers.

The team would fabricate containers for the water to be held in specific to the location along the horizontal stabilizer. The chord length changes along the horizontal stabilizer; therefore, the containers will need to have different lengths. The width of the containers will match the width of the elements used to discretize the distributed load. The containers will be adhered to the horizontal stabilizer and will have fill marks that will indicate different amount of the total load being applied to the structure, for example 50% of the entire load. The load can be added in increments to determine the deflections at different amounts of the total load. A water hose can be used to add water into the containers in between tests. After the desired load is added, the jack stands will be lowered, and the deflections can be measured. The jack stands will then be raised again to support the horizontal stabilizer and the next loading increment will be added and the process will keep being repeated until which is 100% of the load is added.

A part of the designed test fixture is shown below in Figure 19. This test fixture has been designed to model the connection between the horizontal stabilizer and the aircraft which is labeled “Rivet Connection” in Figure 19. The figure also shows how the rivet connection will be welded to a plate which will be connected to the test fixture through bolted connections as shown in Figure 20 and 21.

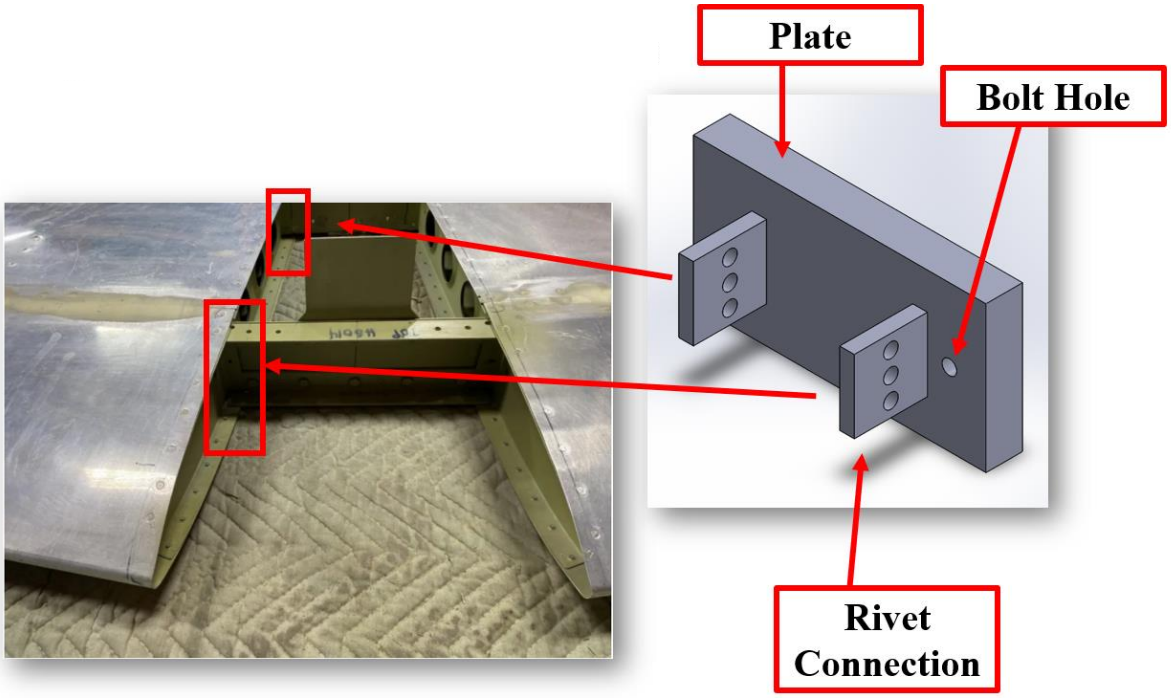

Figure 19: Plate that will connect to the main portion of the test fixture and the horizontal stabilizer.

Figure 20 shows the main portion of the test fixture which will be used to change the angle of attack. The different bolt holes mimic the different angles which we are interested. The different colors represent different angles of attack. Figure 21 represents the assembled test fixture at an angle of attack at -5 degrees.

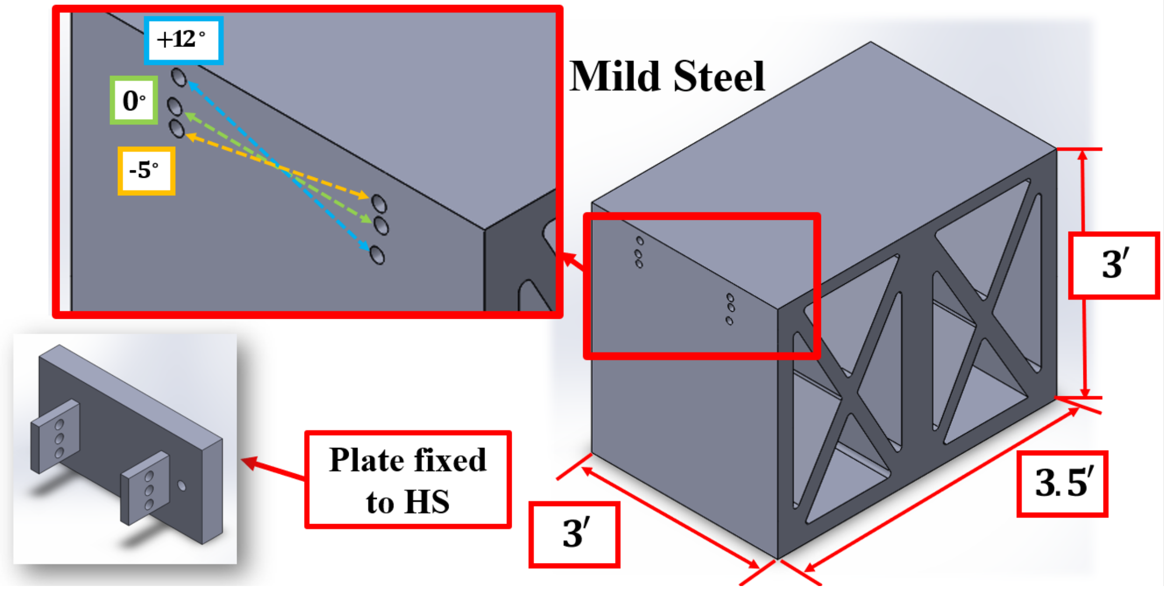

Figure 20: The test fixture for Concept #2.

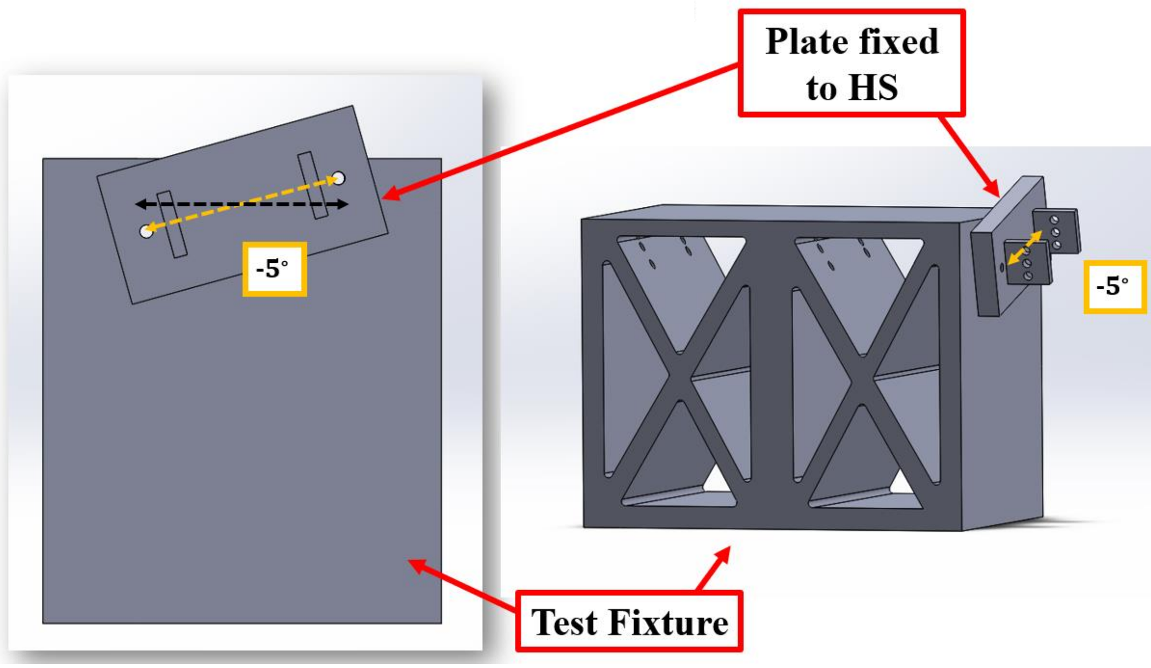

Figure 21: Assembly of the test fixture for Concept #2.

The advantage to this design is that the test fixture mimics how the horizontal stabilizer is connected to the fuselage and it is easy to change the angle of attack of the horizontal stabilizer through bolt connections. It is not difficult to add an exact amount of weight with the water increments and the rulers make it easy to measure vertical and angular deflections. The team can fabricate this test fixture at the Applied Engineering Center (AEC) at the University of Southern Indiana (USI). Some disadvantages of this design are that the rulers may be easy to measure with, but they might not be the most accurate. Also, the water could leak from the containers it will move in the containers as the horizontal stabilizer deflects and it will change the initial loading of the horizontal stabilizer therefore producing inaccurate data. Lastly, the test fixture used the entire horizontal stabilizer so if there is any plastic deformation, we will not have a backup, or it will be difficult to obtain another one to test.

3.3 Concept #3

The third concept has a test fixture that models the entire horizontal stabilizer in a negative-G orientation. The lift force will be modeled using recycled lead put into bags and custom sandbags to match the width of different elements. Dial indicators will be used to determine the deflections. The dial indicators are more precise than rulers and can measure smaller deflections. Strain gauges will be used to measure strain. Foam and strain gauges will be used the same way as described in Concept #1. The third concept is shown in Figure 22.

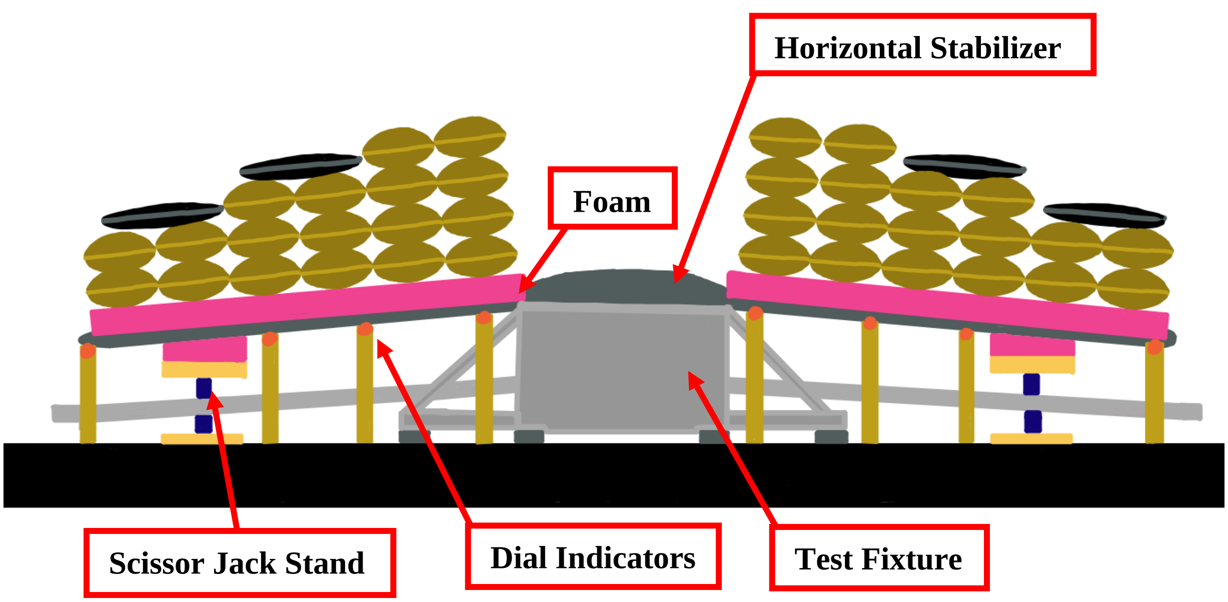

Figure 22: Concept #3.

The test fixture for the third concept will utilize a steel table the team was able to acquire that is very strong and will not deflect during the testing - see Figure 23 below. The table is constructed of a steel and will not deflect under the load being added to the horizontal stabilizer during testing. The table is 3ft 6 inches tall and the tabletop is 2 ft X 2 ft.

Figure 23: Steel Table used for testing the horizontal stabilizer.

The team designed an attachment that will be bolted to the removable tabletop that will change the angle of attach which the horizontal stabilizer is oriented. They can be described as "Wedges", see Figure 24 below. We made the wedges to orient the horizontal stabilizer at -5 and +12 degrees in the negative-G orientation. Negative 5 degrees in the negative-G orientation will require a Wedge that sits the horizontal stabilizer at a positive 5 degrees since we are essentially flipping it upside down. The same goes for positive 12 degree able of attack- the Wedge will have a negative 12-degree orientation. The Wedge will bolt into the tabletop and then the horizontal stabilizer will sit on top of the wedge. The horizontal stabilizer will be bolted into the Wedge the same way it would be bolted onto the fuselage. The horizontal stabilizer without the skin is modeled sitting on top of a set of Wedges in Figure 25.

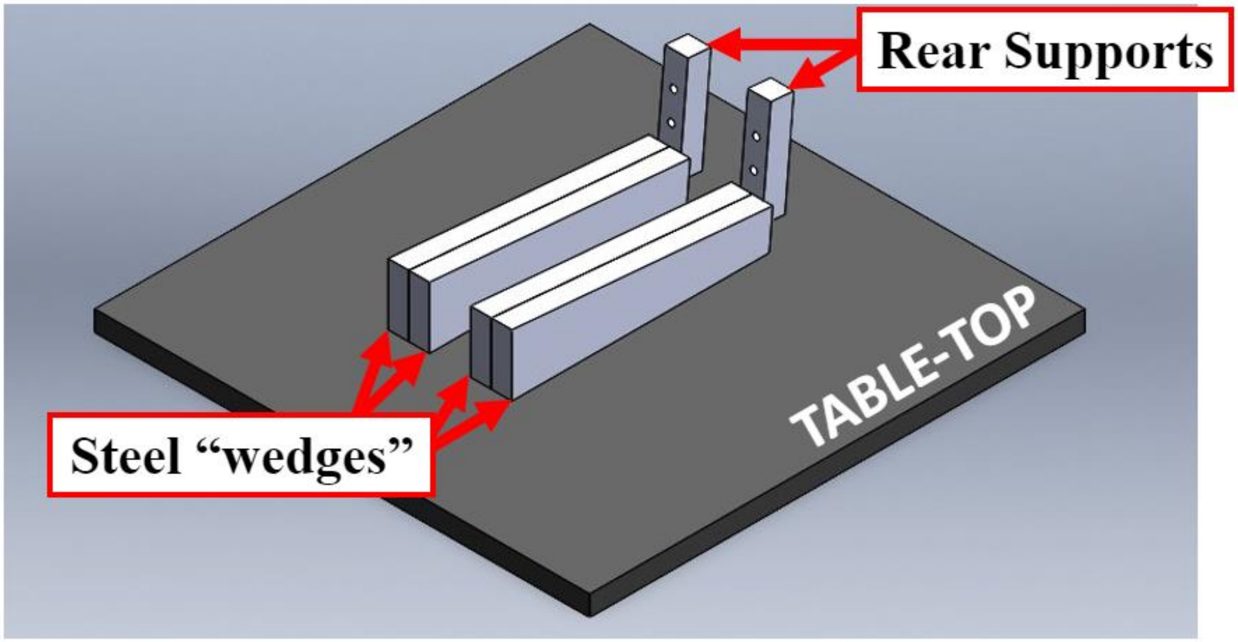

Figure 24: Wedges that bolt to the Table-top and the horizontal stabilizer to model an angle of attack.

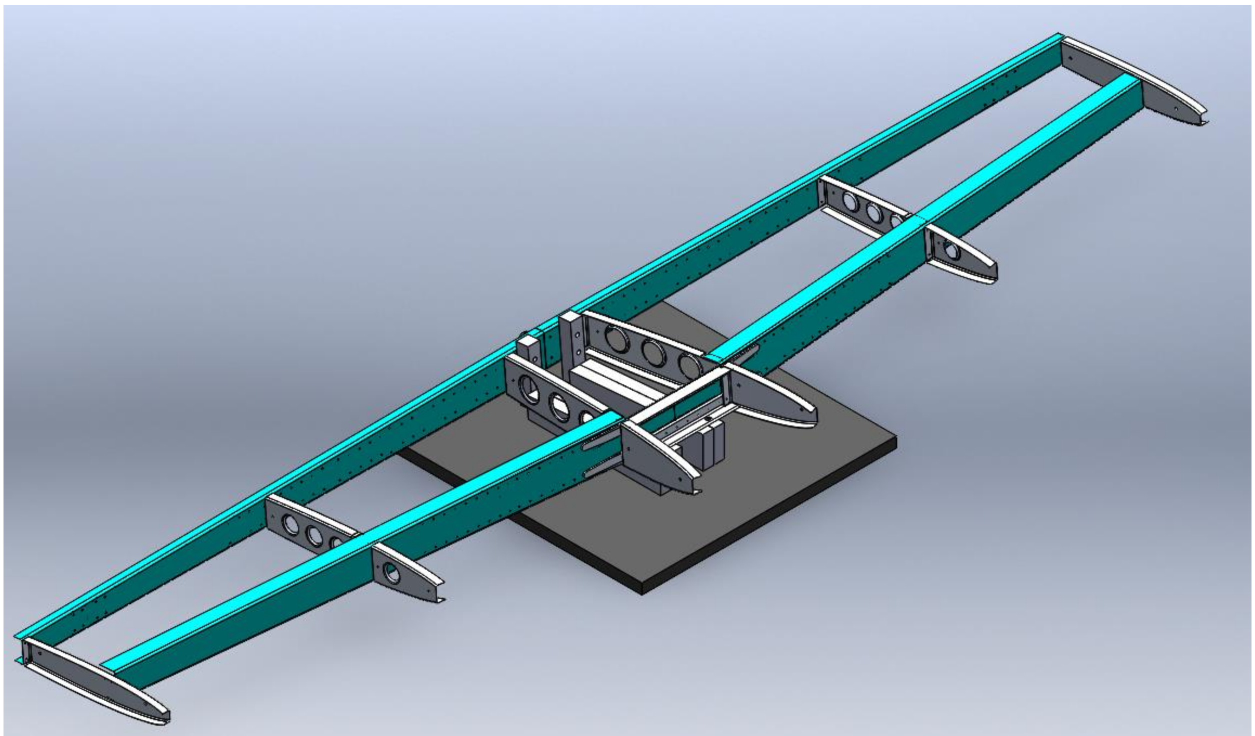

Figure 25: The Horizontal Stabilizer without the skin mounted on top of a set of Wedges that are bolted into the tabletop.

After the horizontal stabilizer is set up, jack stands will be used to support it during testing. The jack stands will sit directly under the horizontal stabilizer by a couple of inches. The purpose of the jack stands is to help counter act any moments that are created from not being able to add the same amount of load on each side of the horizontal stabilizer when testing. The jack stands are also a safety measure for if the horizontal stabilizer were to fail under a given load. The jack stands would catch the horizontal stabilizer and hopefully prevent all the weight that was added to it from falling on anyone.

To measure the deflections, dial indicators will be used at different locations along the horizontal stabilizer on both sides to see both vertical and angular deflection. The team will assemble mounts out of wood for the dial indicators. The dial indicators will be drilled into the wooden mount and will sit about an inch away from the horizontal stabilizer since not much deflection is predicted from the Engineering Design Analysis (Section 4). Bags of lead and sand will be used to create the specific amounts of load needed to be added to each section.

The advantages of the third concept include: easy assembly, easy testing, and a stable base. The text fixture can be broken down into four sections for easy assembly,

1. Steel Table
2. Tabletop
3. Wedges for both angles
4. Square tubing for reinforcement

The testing is simple because the attachments will model the test fixture in a negative-G orientation where the team will just need to add the correct amount of weight directly on the underside of the horizontal stabilizer. And lastly, this is our most stable design with the extra base support attachments to prevent the test fixture from tipping under a heavy load. The disadvantage of this concept is that it takes up a lot of space since it uses the entire horizontal stabilizer. If the horizontal stabilizer were to plastically deform on both sides, it may be impossible to get another one to test.

The concept the team chose was concept #3. This concept was chosen due to is extra stability but as well as its simple design. There are many different reasons why concepts #1 and #2 were not chosen. The main concern with concept #2 was that the water containers could tip over and splash the entire area. Also, they required to have a water hose and a water spigot close, which was not possible when testing at the Applied Engineering Center. On the other hand, Concept #1 required to use a wall, and it was not possible to use the walls of the Applied Engineering Center or Frazier Aviation facilities. Also, the team wanted to test the entire horizontal stabilizer to have more measurements and symmetrical loading. Moreover, the use of strain gauges was limited because the university did not have the necessary equipment to use these. For all the previously mentioned reasons,Cconcept #3 was the most cost-effective and feasible concept to pursue.

4. Engineering Design Analysis

To estimate the lift distribution needed to add to the horizontal stabilizer to mimic operating conditions, the team developed a MATLAB code using thin air-foil theory as explained below. Additional MATLAB code was written to predict vertical and angular deflection. Finite Element Analysis was also completed on the stabilizer to verify the calculations.

4.1 Aerodynamic Load Modeling

The F1 Rocket aircraft horizontal stabilizer has a NACA 0009 airfoil. The numbering system for the NACA airfoils correlates with the geometry of the airfoil and using this information one can decide how to analyze the airfoil. The NACA 0009 airfoil can be seen below in Figure 26. For the given airfoil, the first two numbers of 0009 mean the airfoil is symmetric along the x axis and the last two numbers refer to the thickness of the airfoil [10]. The leading edge of an airfoil is the part of the horizontal stabilizer that meets the oncoming air first and the trailing edge is the rear of the horizontal stabilizer. The chord line of an airfoil runs from the leading edge to the trailing edge and the length of the chord line is the chord length.

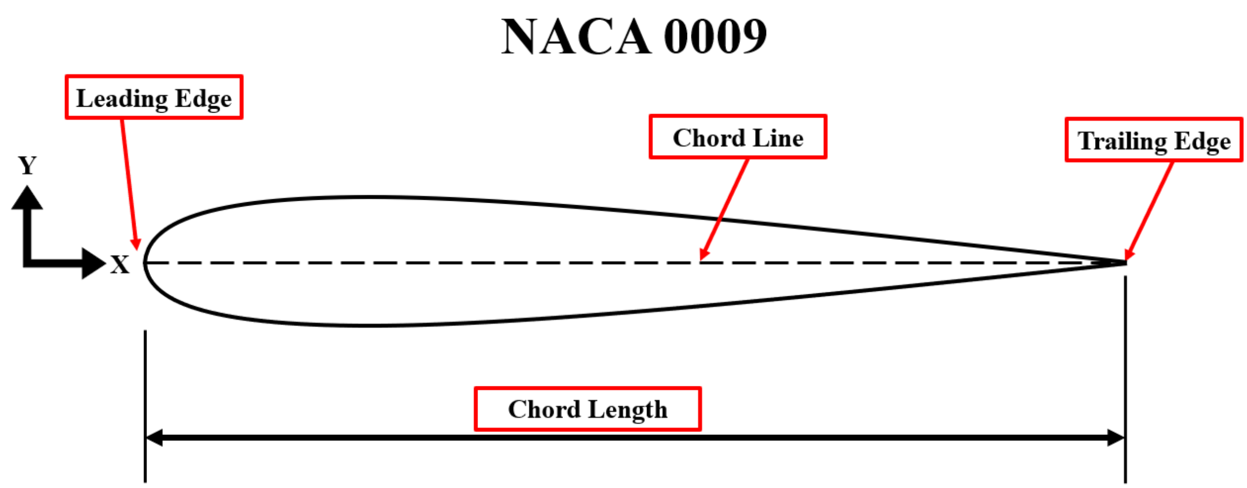

Figure 26: A NACA 0009 airfoil with nomenclature.

The NACA 0009 is a symmetric airfoil and sufficiently thin such that thin airfoil theory can be used. Thin airfoil theory provides relationships to determine the lift forces and different angles of attack at different speeds [10]. Figure 27 below shows the angle of attack, an example lift force distribution, the free stream velocity (V_∞), and an aerodynamic center of an airfoil. The aerodynamic center is the point where the moment caused by the lift distribution remains nearly constant for any angle of attack.

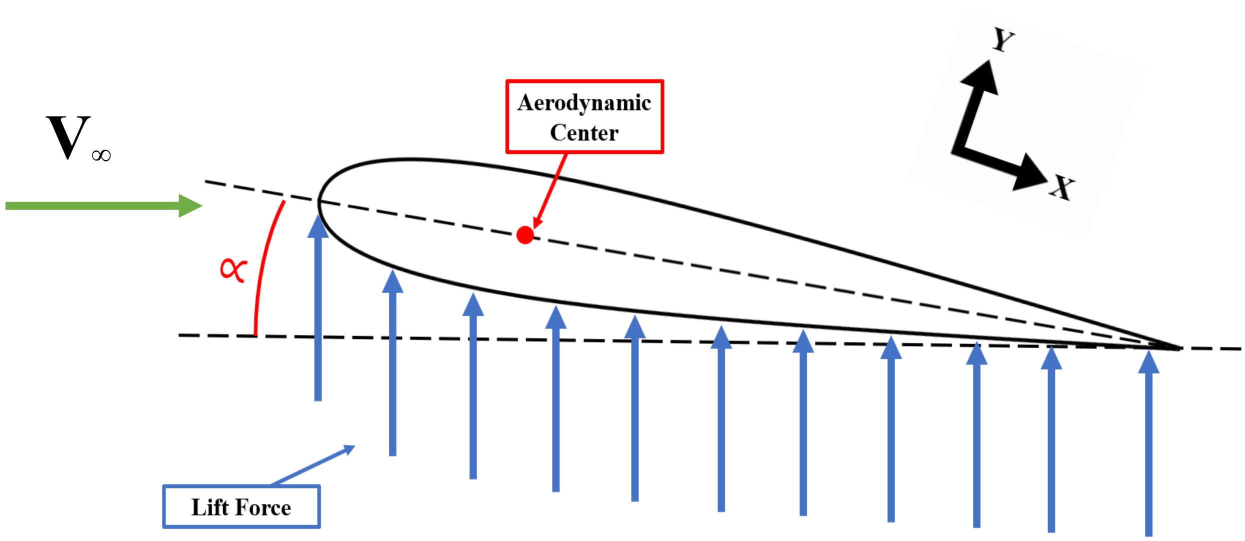

Figure 27: An example of a lift force distribution applied to the HS at an angle of attack and position of the aerodynamic center.

One of the results of thin airfoil theory analysis is that for symmetric thin airfoils the aerodynamic center and the center of pressure is exactly a quarter of the chord length from the leading edge [10]. Thin airfoil theory also provides a simple relationship between the lift coefficient for a 2D wing section, and the angle of attack as shown in Equation 1 where c_l is the section lift coefficient for the airfoil and $\alpha,$ is the angle of attack in radians [10]. The section lift coefficient will later be used determine the lift force distribution.

$$c_l = 2\pi\alpha \tag{1}$$

While drag also occurs on the airfoil in addition to the lifting force, the magnitude of the drag is considered negligible enough compared to the lift to be disregarded in the analysis. Figure 28 is a free body diagram modeling the lift and drag forces being applied to the horizontal stabilizer. It is important to note that the lift force is a distributed load along the bottom surface of a horizontal stabilizer but can equivalently be represented as a "force and moment system [with] the lift acting through any point on the plate and giving the moment at that point." [10] The pitching moment at the aerodynamic center is 0 per thin airfoil theory for thin symmetric airfoils and since drag is small compared to the lift, our model will focus on obtaining the lift force at the aerodynamic center [10].

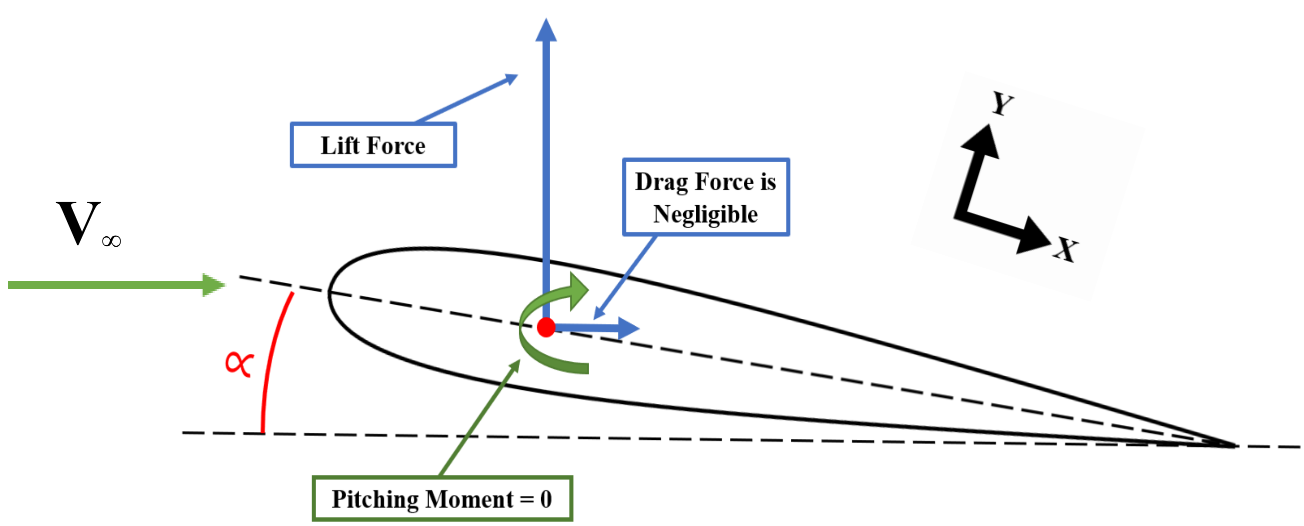

Figure 28: Free Body Diagram of a horizontal stabilizer.

Figure 28 above gives the free body diagram for a horizontal stabilizer in flight at a given angle of attack that is not zero. When the angle of attack is 0, the lift force is also 0 meaning there is no lift force or pitching moment and the drag is negligible. The team made the decision to enable the angle of attack of the horizontal stabilizer to be adjustable in the test fixture during experimentation to minimize complexity, as a purely vertical load representing the lift could be applied on the wing. If the horizontal stabilizer were always at a zero-degree angle of attack in the test fixture, we would need to account for a normal force and an axial force that would be equivalent to the lift force. This would complicate the testing set by requiring loads in two different directions. Figures 29 and 30 below model the normal and axial forces instead of having lift and drag forces.

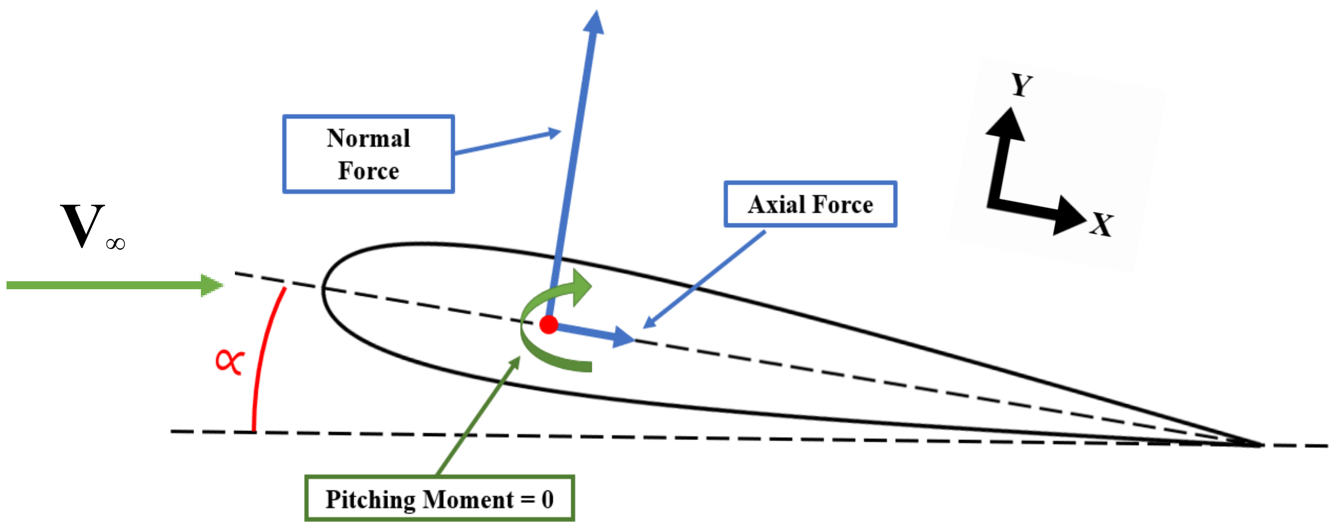

Figure 29: Alternative Free Body Diagram of a horizontal stabilizer with normal and axial forces rather than lift and drag forces pictured.

Since it has been decided to use a test fixture that has an adjustable angle of attack and to consider the drag negligible, calculation of the lift force is the next step. The team has been instructed to find the lift force for angles of attack of -5 to 12 degrees. A MATLAB code was created to determine the lift force for both angles of attack. The complete MATLAB code is in Appendix A, Section 12. An overview of the process the code uses to find the lift distribution is provided here. The constants used in the code are given in Table 1 and some of the defined terms are given in Figure 30. Figure 30 only model's half of the HS since there are two sides. A coordinate system was selected where x=0 corresponds to the root location of the stabilizer. This is indicated in the figure as x=0 and half of the stabilizer is pictured. This half of the stabilizer is divided into 10 elements with 11 nodes at the ends of each element.

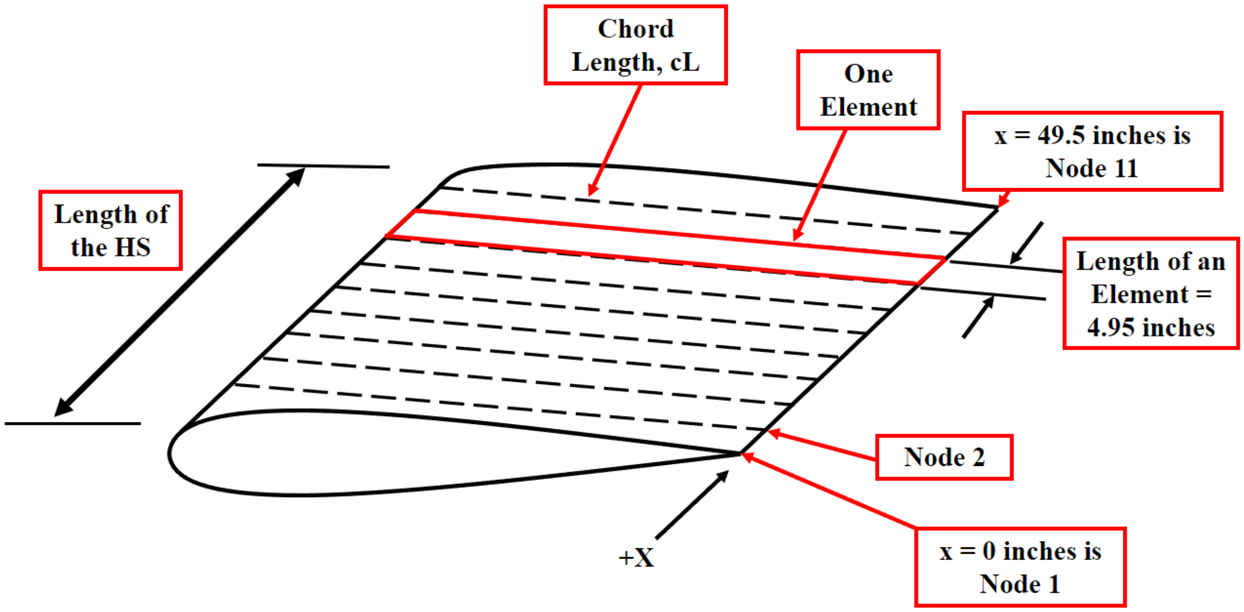

Figure 30: Half of the horizontal stabilizer with 10 elements and defined terms.

Table 1: Constant values used throughout the MATLAB code.

Constant	**Value**
Density (ρ) of air 10,000 ft above sea level	0.001756 ($\frac{\text{slug}}{ft^3}$)
Velocity at 280 mph (V)	410.667 ($\frac{ft}{s}$)
Dynamic Viscosity (μ)	$3.534\text{x}10^{-7}$ ($\frac{\text{slug}}{ft-s}$)
Gravity (g)	32.2 ($\frac{ft}{s^3}$)
Length of the HS (L)	49.5 (in)
Number of Elements (n)	10
Number of Nodes	11
Length of an element (l)	4.95 (in)

E (Modulus of Elasticity of Al T6064)	9.9 $*10^6$ (psi)

The lift force per unit length is a function of the dynamic pressure (q), chord length (cL), and lift coefficient (c_l) [10]. The section lift coefficient equation was given in Equation 1. The dynamic pressure, q, is defined in Equation 2 [10].

$$q = 0.5\rho V^2 \tag{2}$$

With the values in Table 1 the dynamic pressure, q, is found to be 12.34 slug/(in*s^2). The lift force per unit span, F_{Lift}, is defined in Equation 3. [10]

$$F_{Lift} = c_l \, q \, cL \tag{3}$$

The Lift Force per unit span at was calculated at each node and translated to the load needed for each element. Figures 31 and 32 show the lift force distribution calculated at each node in pounds per ft. To find the force that will be added to each element, the force distribution at two adjacent nodes were averaged and multiplied by the element length between them to get a weight in pounds. The force for each element can be found in Tables 2 and 3 for both angles of attack. This lift force distribution along the span of the horizontal stabilizer plotted in the figure is an estimate of the actual lift distribution from the 2D section lift coefficients. The actual lift force distribution needs to include the effects of the finite length of stabilizer which will exhibit other phenomena such as air slipping over the end of the wing. However, these effects tend to lower the overall lift, resulting in the analysis presented here slightly overestimating flight loads.

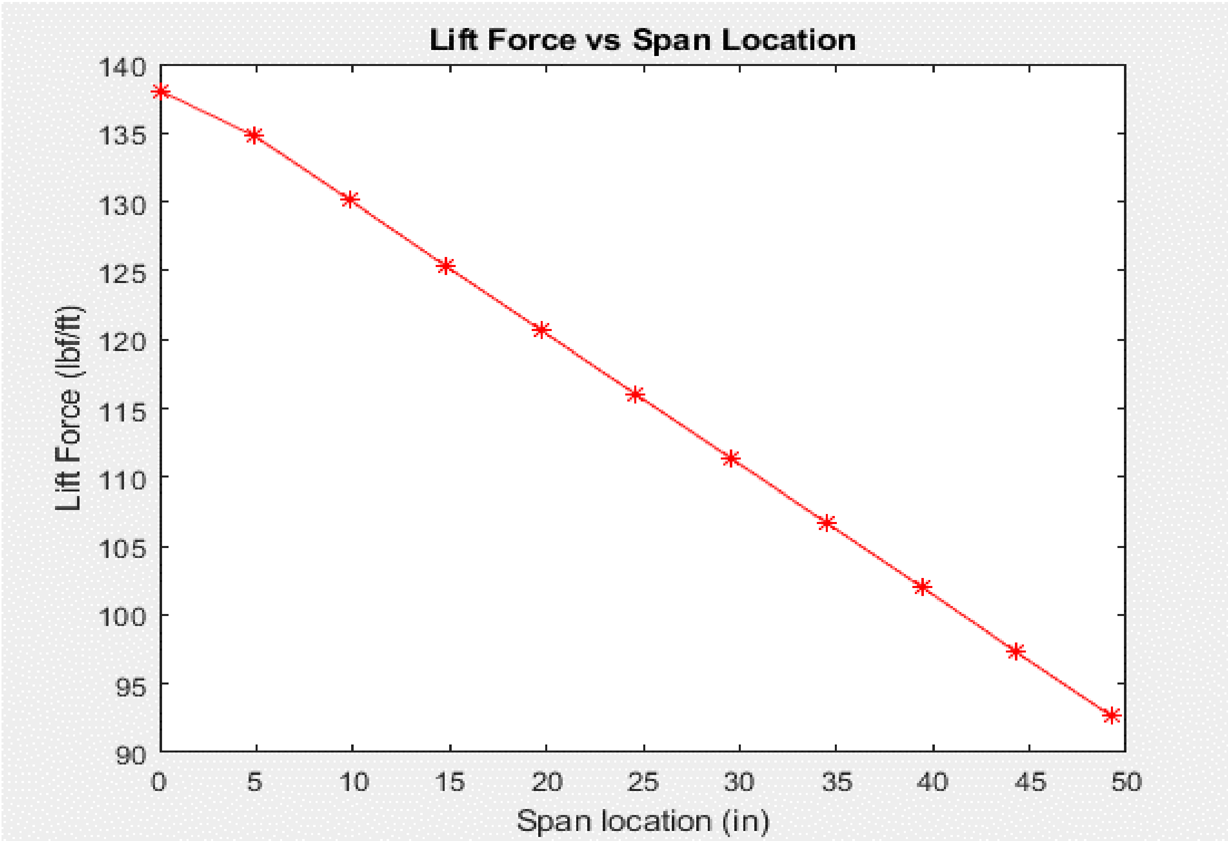

Figure 31: Lift Force calculated for each node for an angle of attack of negative 5 degrees.

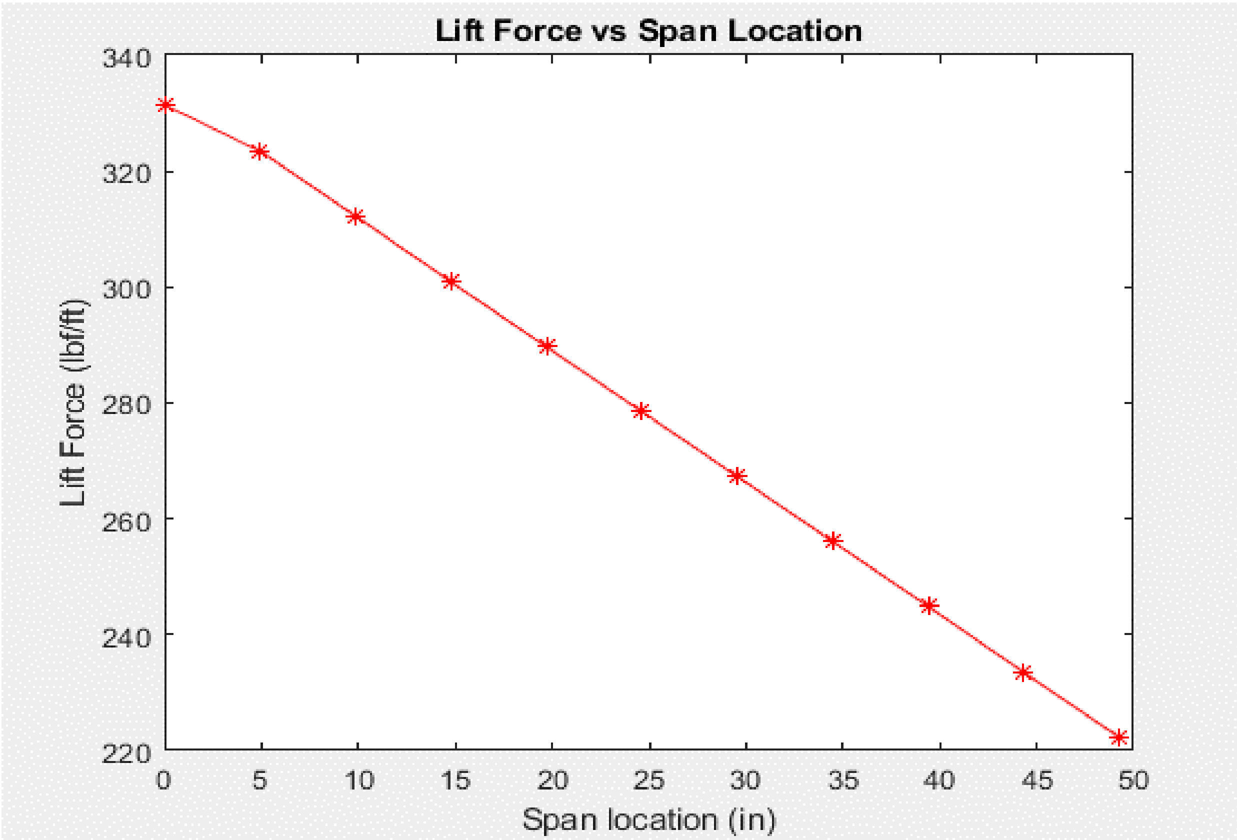

Figure 32: Lift Force calculated for each node for an angle of attack of positive 12 degrees.

Table 2: Lift Force applied to each element for an angle of attack of negative 5 degrees.

Element	1	2	3	4	5	6	7	8	9	10
Lift Force (lbs)	84.8	82.4	79.5	76.6	73.7	70.8	67.9	65	62.2	59.2

Table 3: Lift Force applied to each element for an angle of attack of positive 12 degrees.

Element	1	2	3	4	5	6	7	8	9	10
Lift Force (lbs)	203.4	197.8	190.9	183.9	176.9	170.0	163	156	149.2	142.2

The total calculated lift being applied to each side of the HS is 723.3 lbs for -5 degrees and 1733.5 lbs for 12 degrees.

4.2 Vertical Deflection Modeling

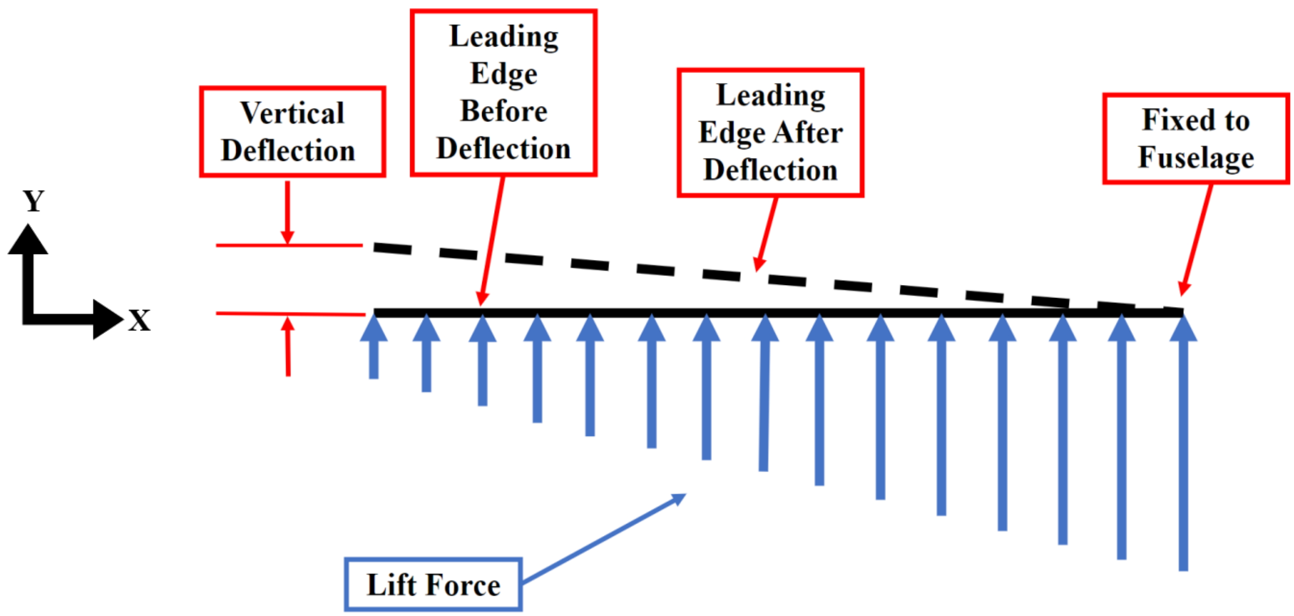

Figure 33: Vertical deflection of a horizontal stabilizer along the length of the structure.

To find vertical deflection, multiple numerical integrations must be completed, the first being shear from the lift force distribution using Equation 4 where x is the position along the leading edge of the horizontal stabilizer starting at the location closest to the fuselage [11].

$$V(x) = \int F_{Lift}\, dx \tag{4}$$

From the shear, the bending moment, M(x), can be calculated using Equation 5 [11].

$$M(x) = \int V(x)\, dx \tag{5}$$

Using the bending moment, the slope of the beam can be calculated using Equation 6 where I is the 2nd moment of area at each element of the HS [11].

$$\theta(x) = \int \frac{M(x)}{EI}\, dx \tag{6}$$

This form is not accounting for asymmetry in the bending, but this can be explored in future work. A computer-aided drafting (CAD) file of the horizontal stabilizer provided to the team was used to find the 2nd moment of inertia at each node cross section. Now, from the slope, the vertical deflection can be determined using Equation 7 [11].

$$w(x) = \int \theta(x)\, dx \tag{7}$$

The predicted vertical deflections at each node are reported below in Table 5 and 6.

Table 4: Vertical deflections along the length of the horizontal stabilizer for a negative 5-degree angle of attack at 250 Knots.

Node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Span Location (inches)	0.00	4.95	9.90	14.85	19.80	24.75	29.70	34.65	39.60	44.55	49.50
Deflection (inches)	0	0.0022	0.0086	0.0185	0.0316	0.0471	0.0644	0.0830	0.1025	0.1226	0.1428

Table 5: Vertical deflections along the length of the horizontal stabilizer for a negative 12-degree angle of attack at 250 Knots.

Node	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Span Location (inches)	0.00	4.95	9.90	14.85	19.80	24.75	29.70	34.65	39.60	44.55	49.50
Deflection (inches)	0	0.0053	0.0205	0.0445	0.0759	0.1132	0.1546	0.1992	0.2461	0.2941	0.3426

4.3 Shear Center and Angular Deflection Modeling

To analytically find the shear center of the horizontal stabilizer, a shear flow method was used from the textbook "Aircraft Structures" by THG Megson [12] The code is given in Appendix A, Section 12, but for full details of how the method works, the reader is referred to the text. Below is Figure 34, where the predicted shear center is along the length of one side of the horizontal stabilizer starting at x = 0 inches (node 1) to x = 49.5 inches (node 11), where the coordinate system is located at the midpoint of the rear spar of the stabilizer with the positive z-axis pointing towards the trailing edge. So, at node 1, the shear center is located at ~6 inches from the rear spar; at node 11, the shear center is located ~4 inches from the rear spar.

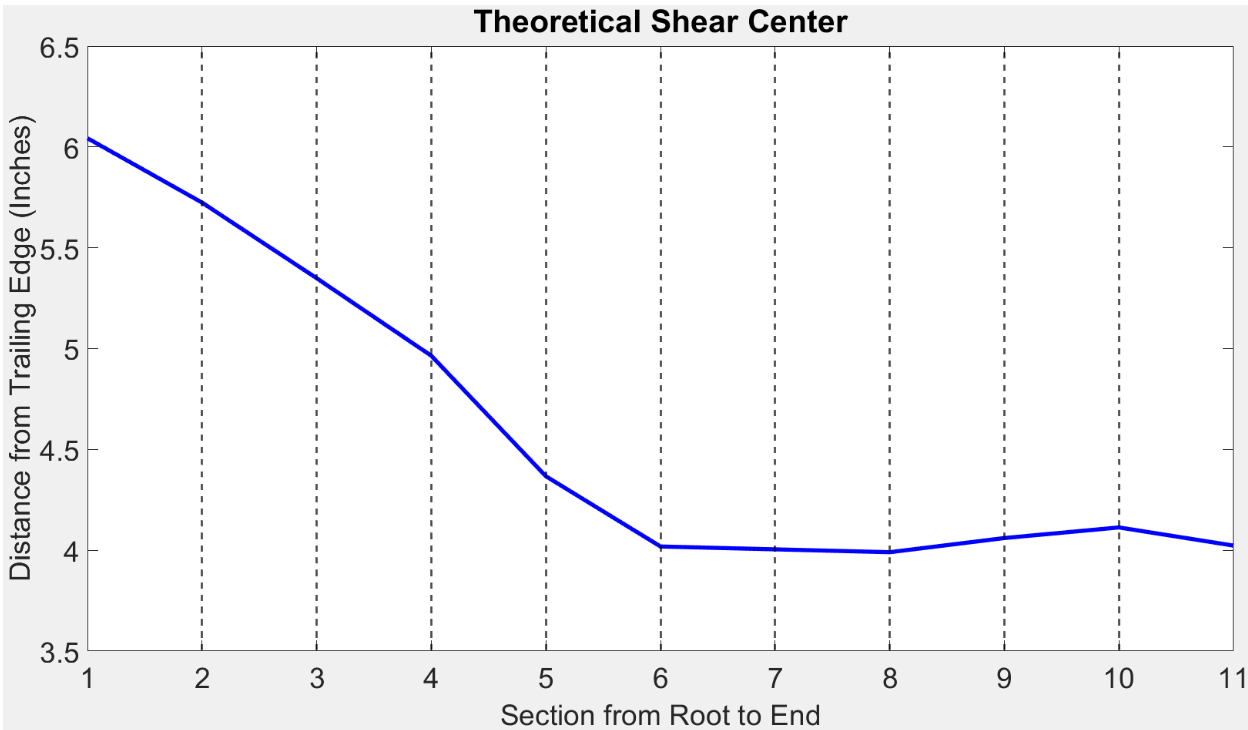

Figure 34: Theoretical Shear Center if the horizontal stabilizer from the Trailing Edge.

With the location of the shear center predicted by the model, the aerodynamic loads can be applied along the quarter-chord consistent with thin air-foil theory and the angular deflection can be predicted using the shear flow model. This can be done for both the 5-degree and 12-degree angles of attack at 250 Knots, resulting in the following plots of the angle of twist of the stabilizer from the root location at x=0 to the tip of the stabilizer at x=49.5 inches. Figures 35 and 36 give the twist in degrees for -5- and 12-degree angles of attack at 250 Knots respectively.

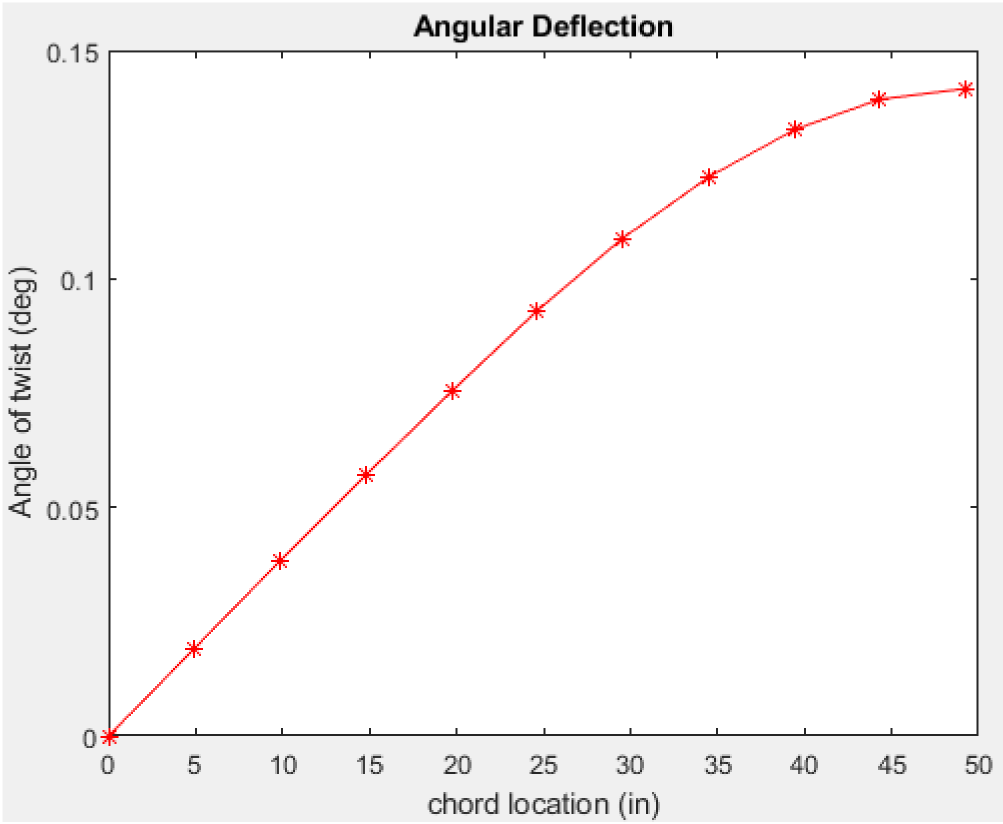

Figure 35: Theoretical angular deflection in degrees for -5-degree angle of attack at 250 Knots.

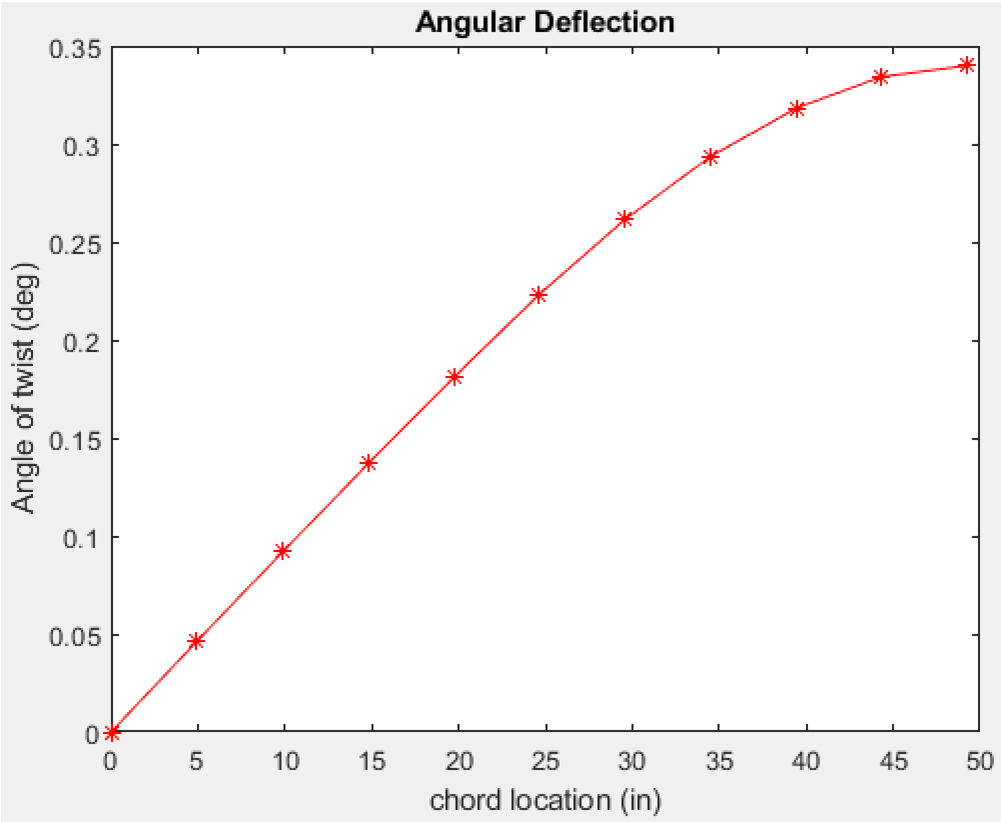

Figure 36: Theoretical angular deflection in degrees for -5-degree angle of attack at 250 Knots.

4.4 Finite Element Deflection Analysis

Half of the horizontal stabilizer was modeled as a cantilever beam, with the lift force applied to the ribs, and front and rear spars. The green arrows in Figures 37 and 38 represent the fixed boundary conditions, and the pink arrows are the lift force. The maximum deflection of the horizontal stabilizer was 2.052 inches on the inside flange of the front spar, but approximately 1.75 inches at the tip of the horizontal stabilizer. Future finite element modeling should include applying the lift force directly to the quarter-chord and shear center, for comparison with experimental and analytical data.

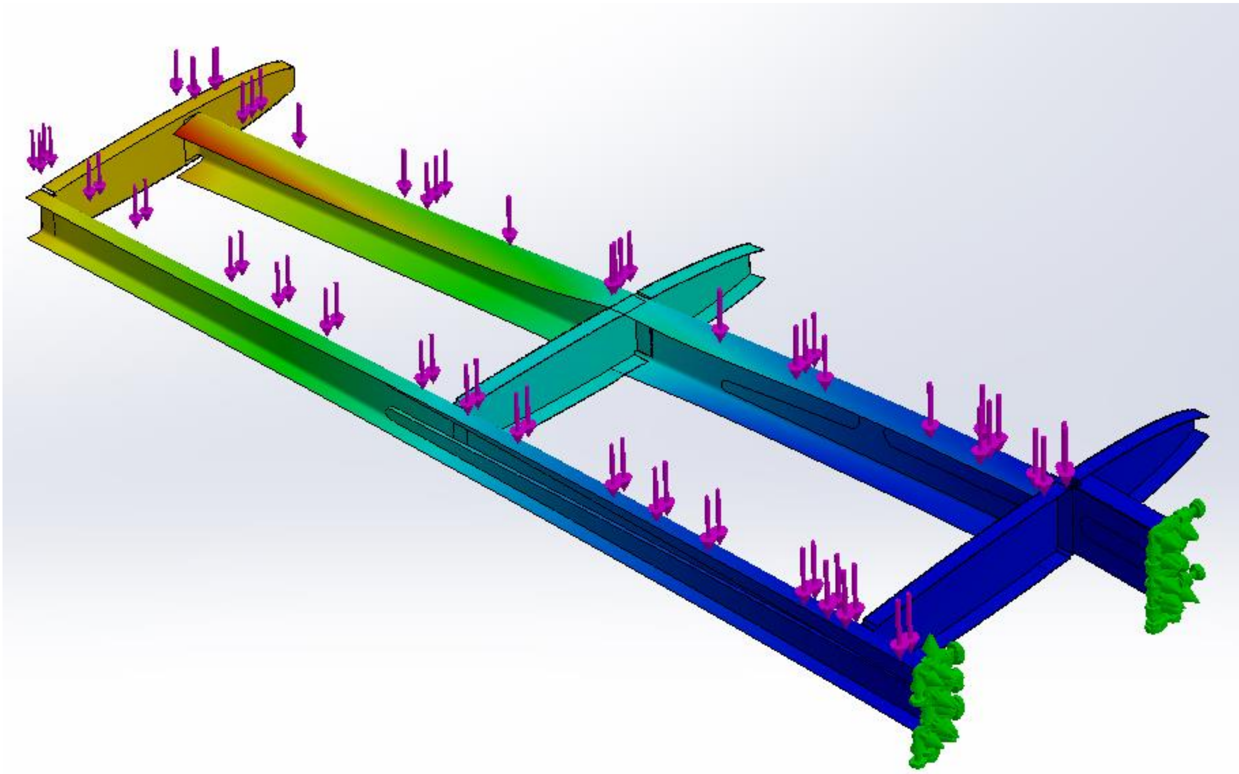

Figure 37: Isometric view of the horizontal stabilizer under a load for a 12-degree angle of attack at 250 knots.

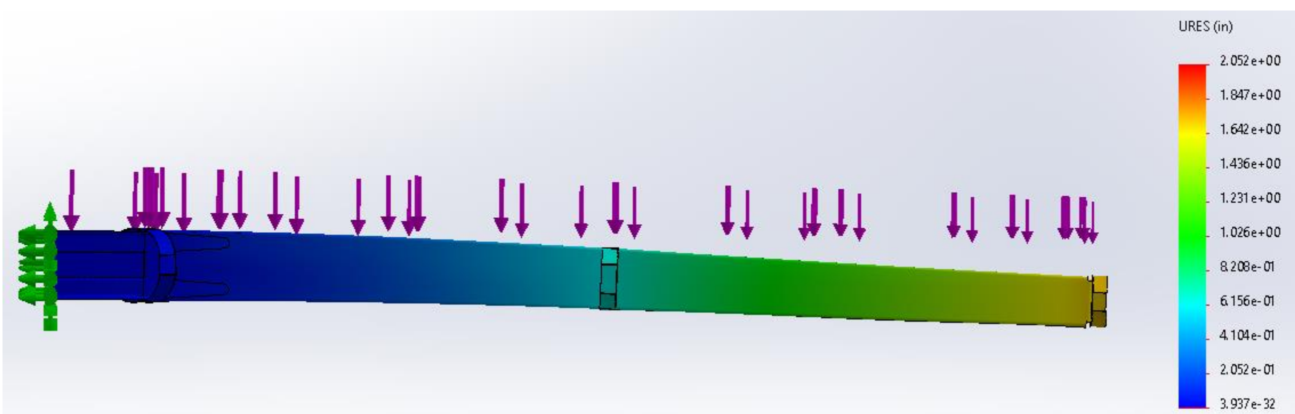

Figure 38: Front view of the horizontal stabilizer under a load for a 12-degree angle of attack at 250 knots.

5. Testing and Procedures

Testing of the horizontal stabilizer includes finding the shear center locations along the chord length, testing for vertical and angular deflection for aerodynamic loads centered over the quarter chord and shear center, and testing to failure.

5.1 Shear Center Testing

The shear center location along the length of the stabilizer was found experimentally. The shear center is the location in the cross section where if the load is applied in that location, there will be no angular deflection (twist). The horizontal stabilizer was attached to the negative 5-degree Wedges to determine the shear center. It was decided to use 5 elements instead of 10 elements along the span when testing for the shear center location. In this case, the elements are approximately 10 inches in width and marked with masking tape. A 10 inch long and 2-inch-wide lead block was used to find the shear center. Starting with element 1 (x=0 inches to 9.9") the block was placed approximately at the predicted shear center found in the Engineering Design Analysis. There were dial indicators to test for angular deflection at the leading edge and the trailing edge. The block was shifted towards or away from the leading edge until the deflection was the same at both edges, a mark was made at the location of the center of gravity of the lead block to indicate where the shear center was for that element. This was process was repeated for the rest of the elements on one side of the horizontal stabilizer. The results are given later in the report.

Figure 39: Testing for shear center.

5.2 Vertical and Angular Deflection Testing

There are two different set ups for deflection testing with aerodynamic loads. For the first set up the aerodynamic load was placed on the shear center locations. While this is not truly what happens in flight, this test can be used to verify the shear center locations found previously and to separately test vertical deflections from angular deflections as negligible angular deflection would be expected to be observed.

The second set up would be modeling where the load is applied in flight. This would mean adding load to the quarter chord length along the horizontal stabilizer. In this case, there should be both vertical and angular deflection since this is modeling actual flight conditions. The testing procedure for both angles of attack is the same except for the magnitude of the load distributions being applied. The procedure for normal operating conditions and testing to failure is attached in Appendix 120. Below in Figure 40 is when the horizontal stabilizer looked like when fully loaded at the 5-degree angle of attack. The results are presented in the Results section.

Figure 40: Loading at the negative 5-degree angle of attack at 350 Knots.

The deflection on the trailing edge and leading edge was measured using dial indicators. Figure 41 displays this dial indicators set up to measure deflection.

Figure 41: Measuring deflection using dial indicators.

When loading the horizontal stabilizer for the first test at the 12-degree angle of attack, the horizontal stabilizer failed before all the load was applied. Figure 42 below displays this failure while Figure 43 is a zoomed in picture of the rivet that failed.

Figure 42: HS failure during first loading at the 12-degree angle of attack at 250 Knots.

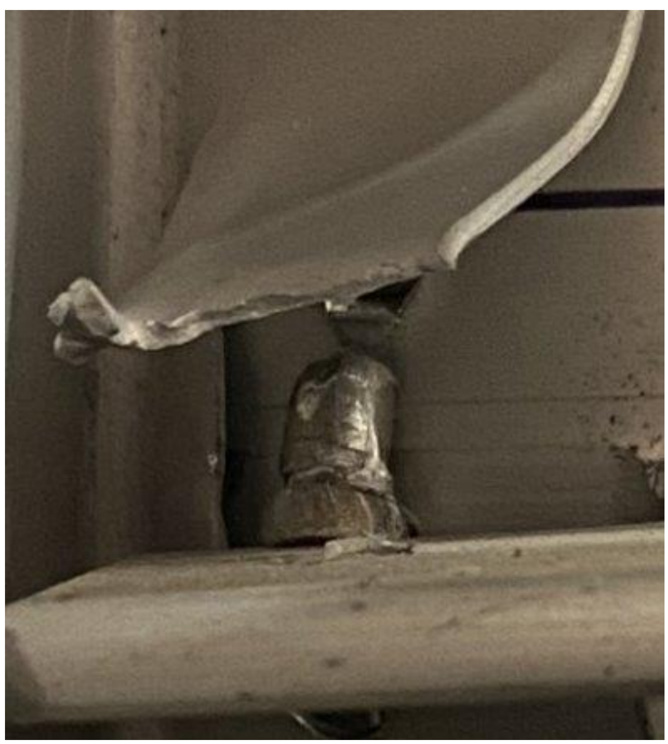

Figure 43: Close up of the failed rivet.

The team was adding a distributed load of 1143 lbf total to both sides of the horizontal stabilizer, but the structure failed at 966 lbf. When the horizontal stabilizer was inspected, it was found that there was a supporting plate missing where the structure failed, as shown in Figure 42. According to the manufacturer, if this supporting plate were installed, this may have prevented the horizontal stabilizer from failing before the entire distributed load was applied. The horizontal stabilizer was repaired, and it was decided to do continued testing with point loads instead of risking failure of the structure again. These point loads provide extra data for future analytical models to be compared to experimental data. This testing is further discussed in the Point Load Testing section.

5.3 Point Load Testing

To further test and gather more data to compare to the analytical models, a point load was added to the last 5 inches of the horizontal stabilizer. Approximately 100 lbf was added for a total of 10 iterations at the shear center and 10 iterations at the quarter chord position. To collect data for this testing, the team used photogrammetry. Pictures of the horizontal stabilizer were taken using two high pixel cameras of the leading edge and the trailing edge. On both the leading edge and trailing edge, there were very tiny dots marked on the horizontal stabilizer to indicate the different points to measure deflection. One set of photos were taken to mark the initial position without any load applied and then a set of pictures after every load was applied. Figure 44 is the photo used to measure the deflection at the trailing edge of the horizontal stabilizer at each point marked in red. Figure 45 a photo after the point load had been applied. Using both photos, MATLAB can measure the distance between the initial and final location of the red dots to give a vertical deflection at each location. The data is presented in the Results section.

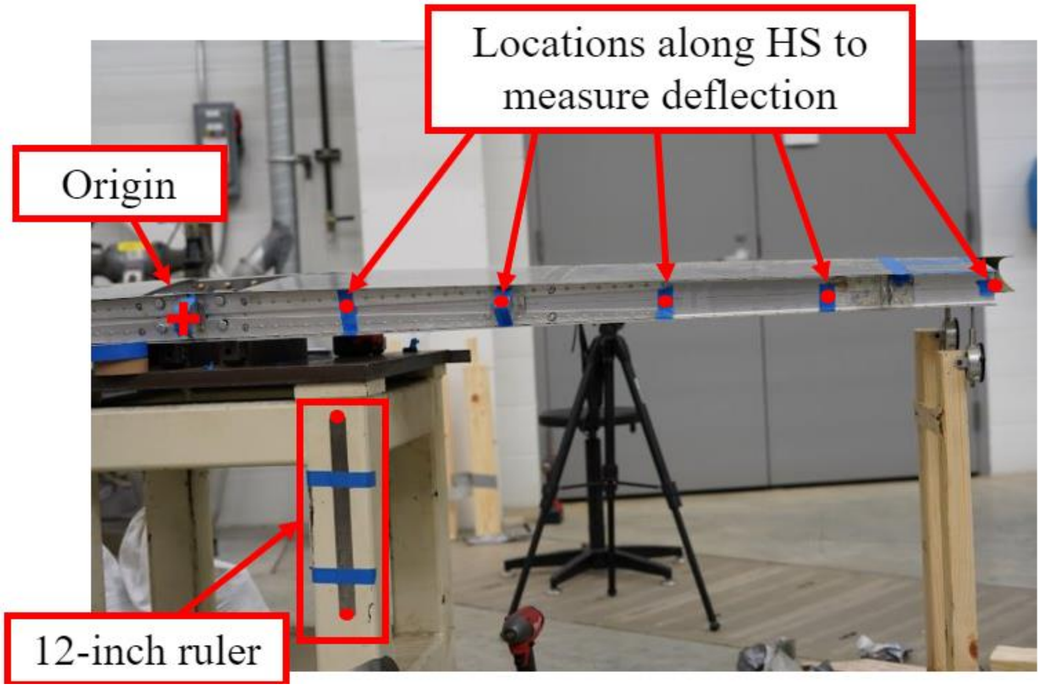

Figure 44: Picture of the Initial Position of the horizontal stabilizer used to measure deflection of the trailing edge using photogrammetry.

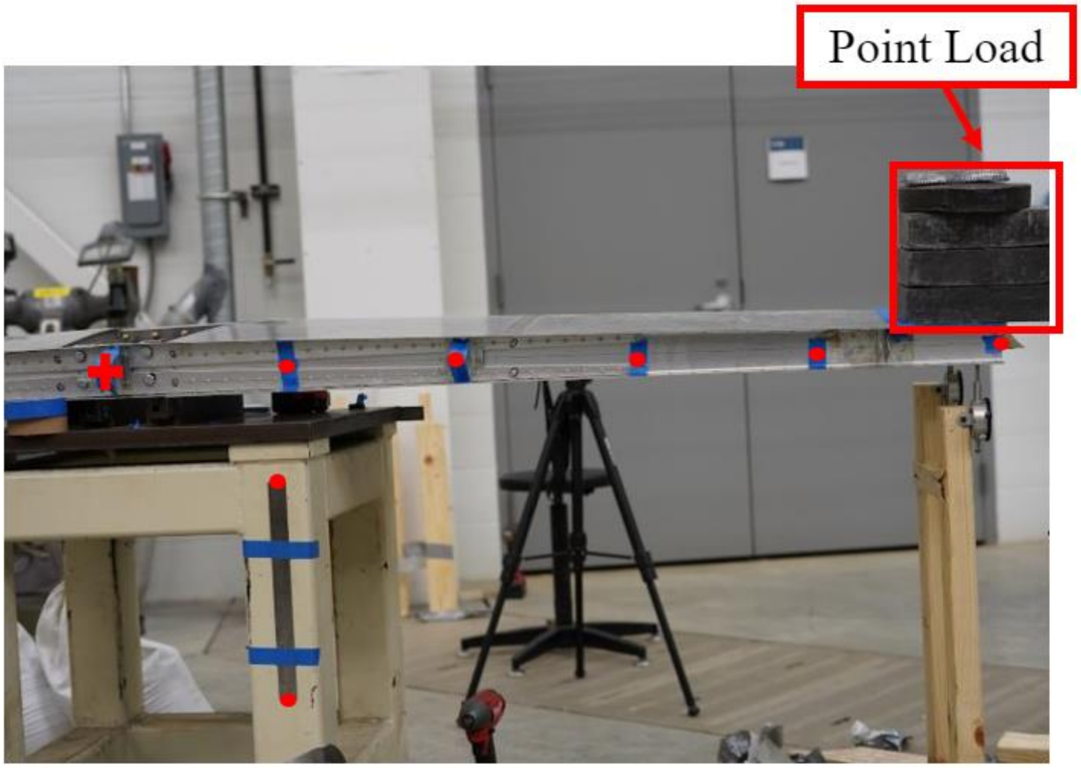

Figure 45: Picture of the one of the iterations of the horizontal stabilizer with the point load added used to measure deflection of the trailing edge with photogrammetry.

6. Results

The results for the shear center comparing the analytical calculation and the experimental result are presented in Figure 46. The results are similar thru nodes 1-7 but differ about an inch to two inches thru nodes 7-11. If we remove the skin from the calculations, it is predicted that the analytical calculations would match up more with the experimental data.

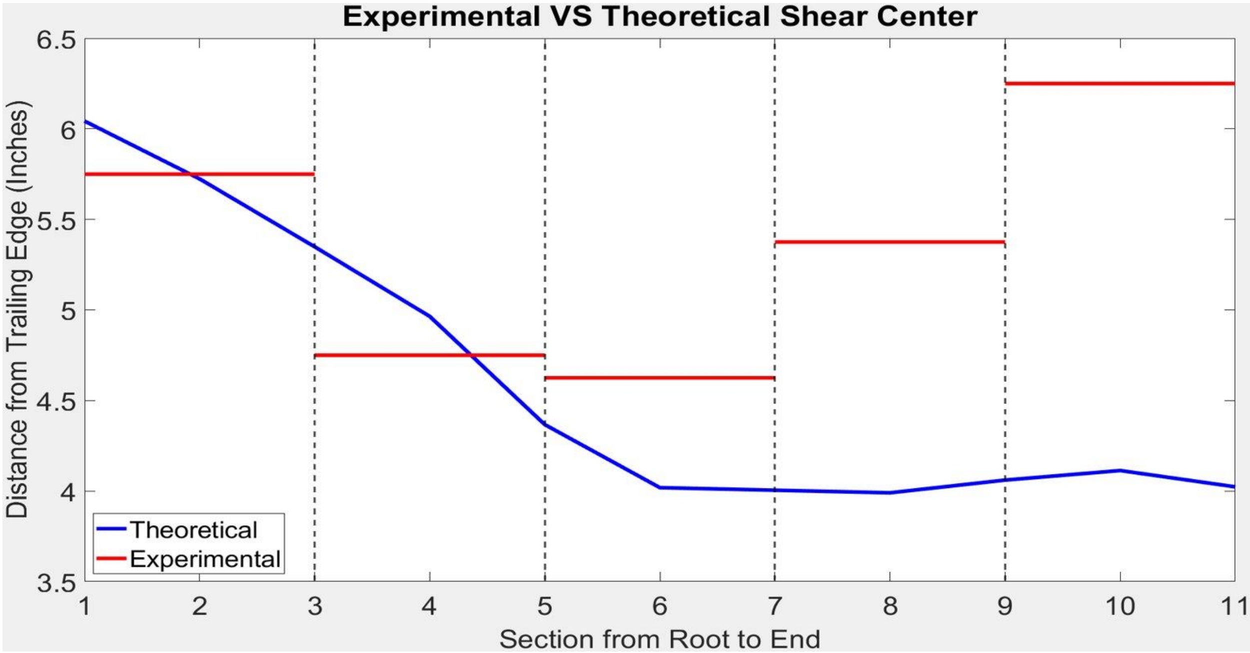

Figure 46: Comparison of shear center results.

There were not analytical calculations for the deflection expected when loading the horizontal stabilizer at the quarter chord, but it was still tested for. When loading on the shear center, it is expected to not twist at all of shear center. The results for loading the horizontal stabilizer with a load representing a -5-degree angle of attack at 250 knots is given below in Table 6. While the twist is not exactly 0 degrees, it is a small angular deflection.

Table 6: Results from loading the horizontal stabilizer on the shear center with a load representing a -5-degree angle of attack at 250 knots is given below.

Shear Center Experimental Results

Deflection (inches)			Twist (degrees)		
A	B	C	A	B	C
0.181	0.489	0.734	-0.23	0.274	-0.06

For the -5-degree angle of attack at 250 knots loaded at the quarter chord, the experimental deflection and twist is given in Table 7 below. The experimental deflection compared to the analytical deflection is given in Figure 47 below. The twist varies by section and twists more at the root and the free end and almost doesn't twist at all in the middle. After discussion, the dial indicators may have not been close enough to the leading edge and the trailing edge to get an accurate measurement for twist. The dial indicators need to be placed at the very outside of the leading and trailing edge and they were more inside of the horizontal stabilizer. If the test was redone, the dial indicator placement would be altered. Notice the experimental deflection greater than the analytical deflection. It is predicted that if the experiment was completed again with the supporting plate installed that the horizontal stabilizer would be stronger, and it would not deflect as much. Therefore, the experimental data would be closer to the analytical models.

Table 7: Results from loading the horizontal stabilizer on the quarter with a load representing a -5-degree angle of attack at 250 knots is given below.

Quarter Chord Experimental Results

Deflection (inches)			Twist (degrees)		
A	B	C	A	B	C
-0.248	-0.299	-0.594	-0.527	-0.017	-0.557

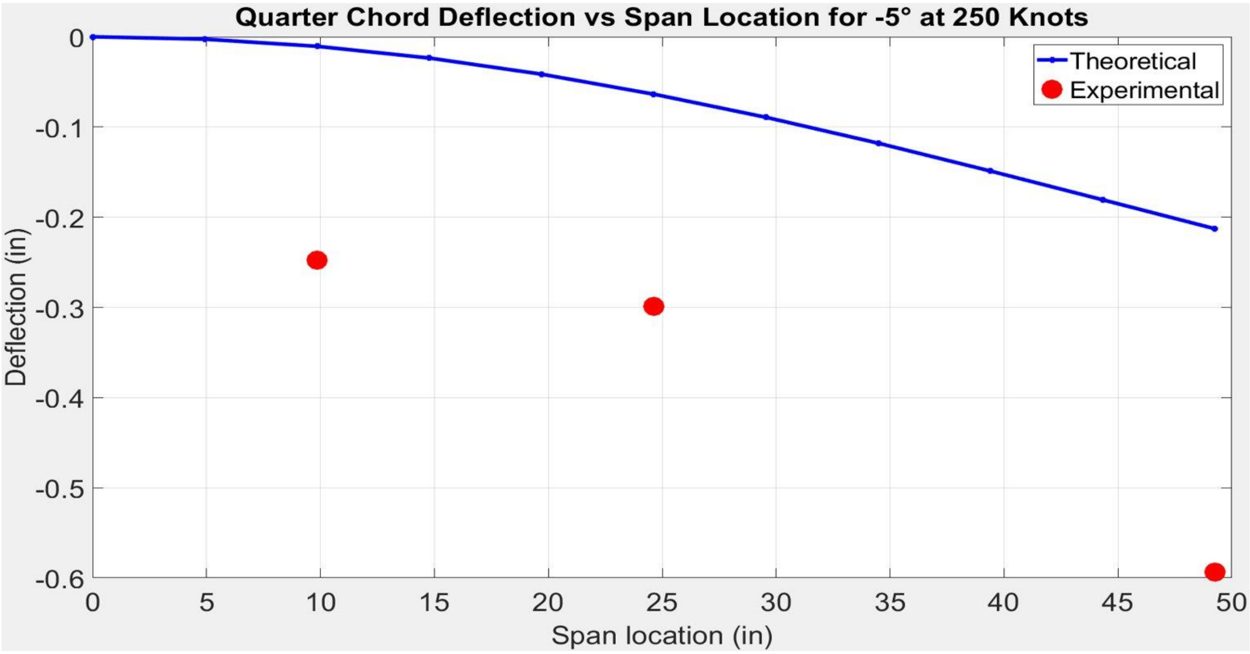

Figure 47: Results from loading the horizontal stabilizer on the quarter chord with a load representing a -5-degree angle of attack at 250 knots is given below.

There was no data collected for the loading of the horizontal stabilizer at a 12-degree angle of attack at 250 knots due to the structure failing. When completing the point load testing, the deflection recorded was around ~0.3 inches based off readings from a few dial indicators that were set up to verify the photogrammetry. The results from photogrammetry have not been computed and are left to future work.

7. Lessons Learned

There were a few lessons learned from this senior design project. They are listed below:

- Complete calculations before deciding methods for testing because we were not prepared to add thousands of pounds of load to each side of the horizontal stabilizer at the beginning of the semester
- Working with steel takes a lot of time
- Good Solidworks models help ensure proper design
- Better communication between the engineer helping with the project as well as the sponsor will avoid set-backs

- Verify the equipment is set up and installed correctly before beginning the experiment
- Verify dial indicator placement is at the leading edge and trailing edge instead of a couple inches inside of the horizontal stabilizer

8. Conclusion

Overall, the team met the objectives and deliverables for the senior design project. Analytical models were created to predict the aerodynamic loads for the -5 and 12-degree angle of attack at 250 knots and then used to predict vertical deflection and twist when loading at the quarter chord as well as predictions for the shear center. The models did not match up perfectly, but the analytical models resembled the experimental models. We predict that if the experiment was completed again with the supporting plate installed that the data would be even more similar. It would also be helpful to make some changes to the analytical models, such as removing the skin from the HS and gathering new values for the 2nd moment of area. The team was able to design and build a reusable text fixture that can be used to complete further testing to keep improving the analytical models using the static load test procedure that the team also created. Recommendations for future testing includes doing more point load testing and communicating the testing plan to the entire team better, as well as using photogrammetry to measure the deflections.

9. References

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10. Appendix A

10.1 System Hierarchy

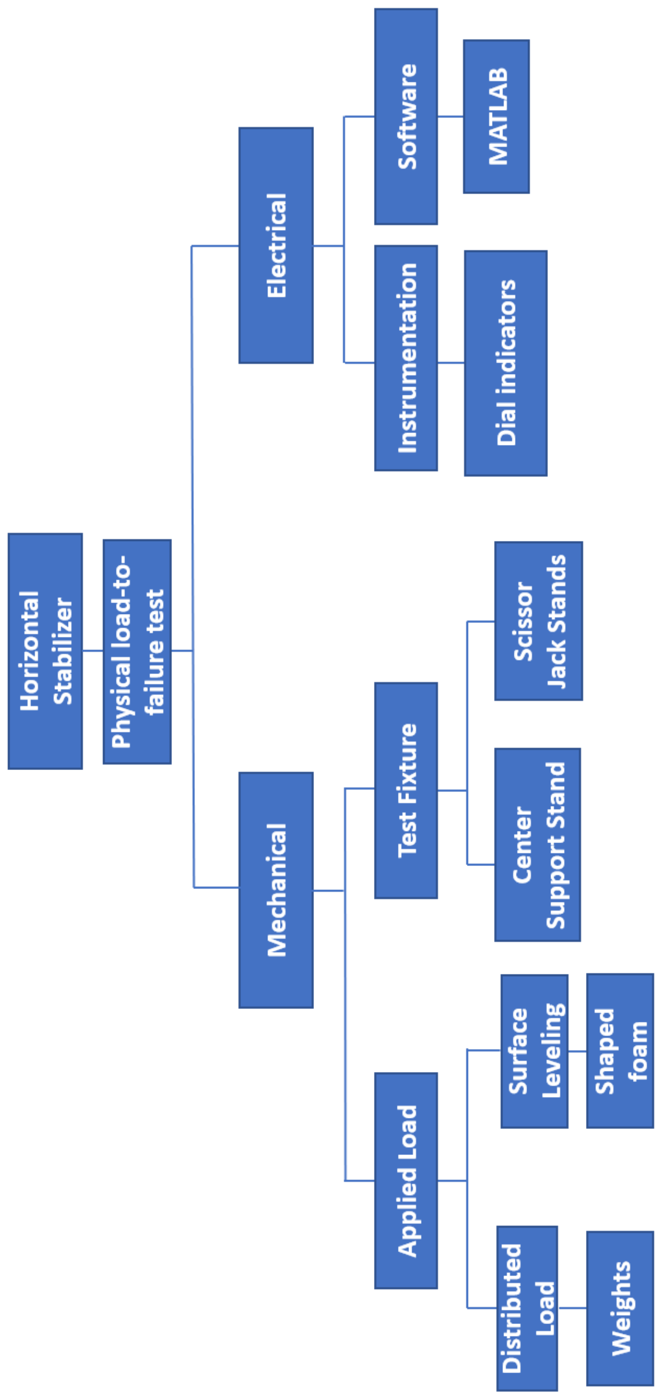


Figure 48: System Hierarchy.

10.2 Schedule

Table 8: The schedule for the senior design project.

Task	Due Date	Completion Date
Spring Semester		
First Meeting with Vince Frazier to determine customer needs	1/28/2021	1/28/2021
First meeting with Paul Romano to determine project requirements	2/9/2021	2/9/2021
First draft of Senior Design Report due	3/12/2021	3/12/2021
Final Senior Design Proposal due	3/22/2021	3/22/2021
Senior Design Proposal Oral Presentation.	3/25/2021	3/25/2021
Determine three conceptual designs	4/14/2021	4/14/2021
Discuss three concepts and chose one a final concept design	4/16/2021	4/16/2021
Continue to work on the Pre-Senior Design Report	4/18/2021	4/18/2021
Senior Design Concept Oral Presentation	4/19/2021	4/19/2021
Begin to build the analytical models in Excel	4/21/2021	4/21/2021
Design a test fixture on Solid Works based on the engineering calculations done and the analytical models	4/25/2021	4/25/2021
Continue to work on the analytical models and do initial calculations	4/27/2021	4/27/2021
Pre-Senior Design Report due	4/30/2021	4/30/2021
Meeting with Frazier Aviation, LLC to discuss next steps	5/7/2021	
Fall Semester		
Begin working on Critical Design Review and Schedule weekly meetings with Dr. Nelson	8/23/2021	
Discuss Critical Design Review with Dr. Nelson	8/23/2021	
Order Materials for the Test Fixture	9/8/2021	
Start Building the Test Fixture	9/23/2021	
Finish building the Test Fixture	9/30/2021	

Start performing static load testing on the horizontal stabilizer	10/6/2021	
Begin analyzing the data and compare physical test results with Analytical models	10/8/2021	
Static Load Test Session #1	10/21/2021	
Static Load Test Session #2 (Extra Testing)	10/22/2021	
Start the Senior Design Report	10/24/2021	
Finish the Analytical models	10/25/2021	
Finish the first draft of the Senior Design Report	11/2/2021	
Start to work on the Senior Design Presentation	11/2/2021	
First draft of Senior Design Report due to adviser	11/8/2021	
Finish the Senior Design Presentation	11/10/2021	
Final Presentation Review	11/12/2021	
Second draft of Senior Design Report due to adviser	11/19/2021	
Complete final corrections to the Senior Design Report	11/22/2021	
Bring the report to the Writers Room to check grammar	11/23/2021	
Submit Project Poster	11/25/2021	
Completed and signed copy of Senior Design Report due to Engineering Department	11/29/2021	
Final Presentation	12/3/2021	
Evening Poster Session	12/10/2021	

10.3 Budget

Table 9: Budget for chosen concept.

Item	Quantity (#)	Cost ($)
Foam Board FOAMULAR 250 XPS, 2-in thick	4 sheets	$ 114.24
Scissor Jacks	2	$ 0.00
Sandbags	20	$ 38.95
Plastic wrap	1 roll	$ 27.98
Safety Tape	1 roll	$ 8.96
Nuts & Bolts	as needed	$ -
2″ x 4″ Whitewood Stud	96 inches	$ 16.88
Hot Rolled Steel Rectangle Bar 1″ x 6″	80 inches	$ 210.58
Strain Gauges	20	$ 178
Dial Indicator	12	$ 30.14
Faculty Labor	10 hours	$ 1000.00
Student Labor	40 hours	$ 750.00
Total Cost	-	**$ 2214.91**

10.4 Requirements

The Analytical models shall…

- Obtain predictions for aerodynamic loads on the HS for angles of attack between 5 and 12 degrees.
- Predict vertical and angular deflection under the applied load distribution.
- Predict the shear center locations along the HS span.
- Ideally have a percent error of less than 10% relative to the experimental data.

The Test Fixture shall…

- Have a corrosion resistant coating.
- Allow the Horizontal Stabilizer to be set up in a negative-G orientation.
- Be reusable.
- Not deflect more than 0.02 inches under the applied load distribution.
- Allow the user to do static load tests at angles of –5° and 12°.

The Static Load Test shall…

- Provide vertical and angular deflection under the given load distribution.
- Not plastically deform the horizontal stabilizer until a test to failure is desired.

10.5 Concept of Operations

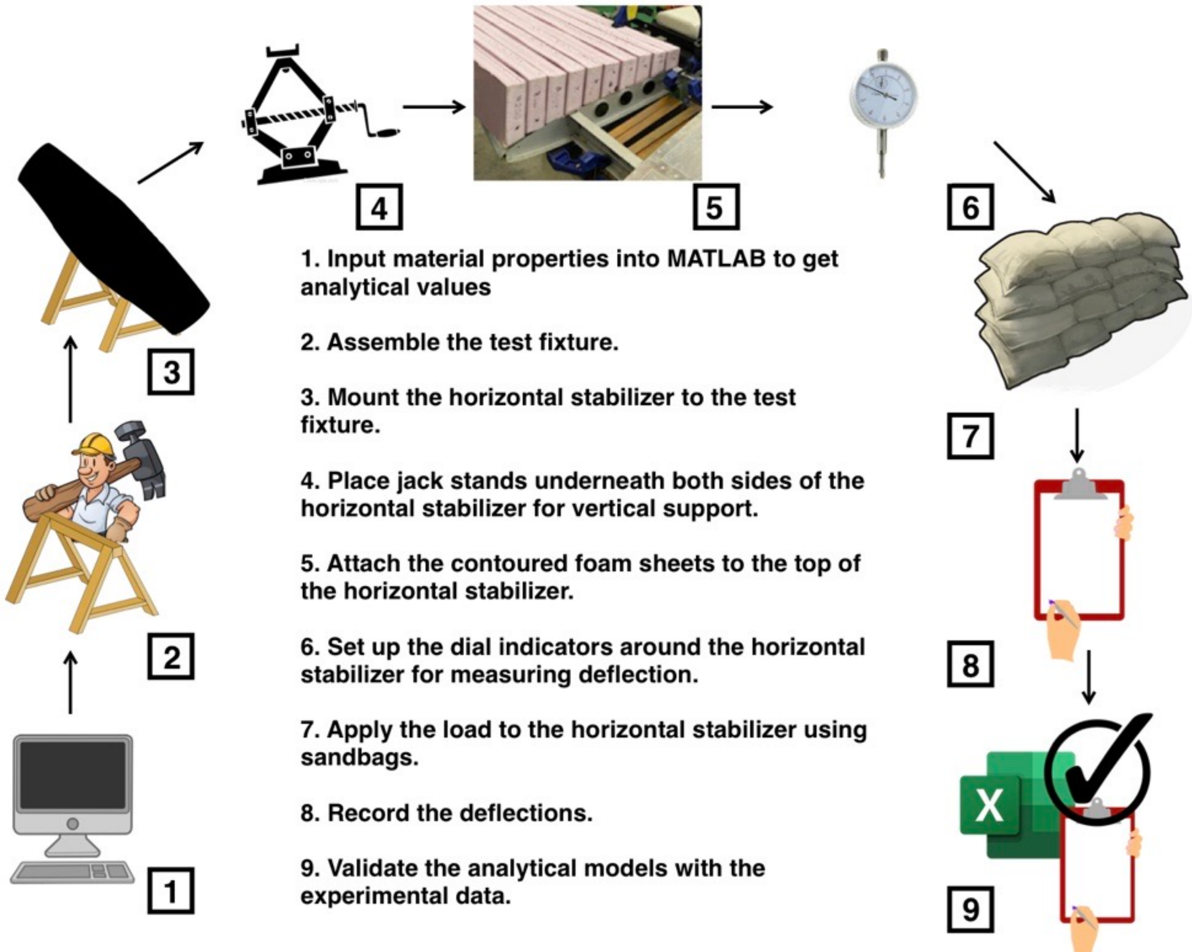


Figure 49: Concept of operations for the chosen concept.

10.6 Failure Modes and Affects Analysis

10.6 FMEA Before December 10th

Table 10: FMEA up to December 10th, part 1.

Item	Failure Modes	Cause of Failure	Possible Effects	Probability	Level	Possible action to reduce failure rate or effects
Jack Stands	Collapse under load	a. Not rated correctly b. defective materials c. not manufactured properly	a. Skewed data b. Injury	Low	Critical	Stack dense pieces of wood under the horizontal stabilizer before it has been loaded so if the jack stand does fail, there is a safety mechanism present. To make sure the data is not skewed, measurements of the height of the horizontal stabilizer should be recorded before load is applied and after load is applied when the horizontal stabilizer is still at the initial height before the jack stands have been released. These values should be the same.
Data Collection	Data is recorded incorrectly	a. Operator error b. rulers and/or grid set up incorrectly	a. incorrect results	High	Very Critical	Multiple people in the group should record data from the rulers and compare answers before moving on to the next step. If we choose to use cameras and rulers, then we will have pictures to compare with if there are still discrepancies. An easy practice test could be done to check if the results match the data being collected.
Data Collection	Camera dies during testing	a. camera does not have a long battery life b. battery is not fully charged before beginning testing c. back up batteries were not used or charged	a. no data collected for the experiment or not all the data collected	Medium	Very Critical	Make a checklist to be followed prior and during the experiment. On the prior checklist, include charging all the camera batteries. During the checklist, check the camera battery periodically throughout the experiment and switch the battery when the battery life drops below 25%. Then begin charging the used battery.

Table 11: FMEA up to December 10th, part 2.

Item	Failure Modes	Cause of Failure	Possible Effects	Probability	Level	Possible action to reduce failure rate or effects
Data Collection	Memory card is lost	a. misplacing the card b. card is stollen	a. not having the data from the experimentation b. redo the experiment	High	Very Critical	Make a checklist to be followed prior and during and after the experiment. For each section of the checklist, track and check where the memory card should be located. To minimize transfer of the memory card, put one group member in charge of keeping the card in a specific place. On the post text checklist, include immediately uploading the data onto a computer and one drive file that is shared with the group.
Data Collection	Grid is slanted	a. not paying attention to detail b. the tape used to hold the grid on the wall slipped and is not holding the grid in the initial position c. the fixture holding the grid up has moved and is not holding the grid in the initial position	a. data is incorrect	High	Very Critical	On a checklist created for before the experiment, have group members check the level of the grid in comparison with the ground to make sure the grid is parallel with the foundation on which the experiment will be conducted. On a checklist created for during the experiment, have group members check the grid level again to make sure the fixture holding the grid up has not moved or the tape holding the grid to a wall has not slipped any.

10.6.2 FMEA After December 10th

Table 12: FMEA after December 10th.

Item	Failure Modes	Cause of Failure	Possible Effects	Probability	Level	Possible action to reduce failure rate or effects
Safety	Customer does not load the test fixture properly	a. does not read the test procedure	a. the HS breaks during testing and the operator gets injured b. the HS permanently breaks	Low	Very Critical	Paint the safety stop a bright red color to help the customer not forget to set it up before testing. Have clear written and video instructions uploaded on a Dropbox file that can be shared with the customer.
Data Collection	Customer does not know how to enter data into the MATLAB code	a. instructions on how to operate the MATLAB code are not clear b. the customer does not read the instructions on how to use the MATLAB code c. the instructions needed to operate the MATLAB code gets lost	a. cannot fit analytical models to be able to perform further analysis	Medium	Critical	Instruction on how to use the MATLAB code can be stored on a Dropbox file that will be shared with the customer. A video instruction can also be uploaded explaining how to operate the MATLAB code and how to interpret the data it gives.

10.7 Mechanical Block Diagram

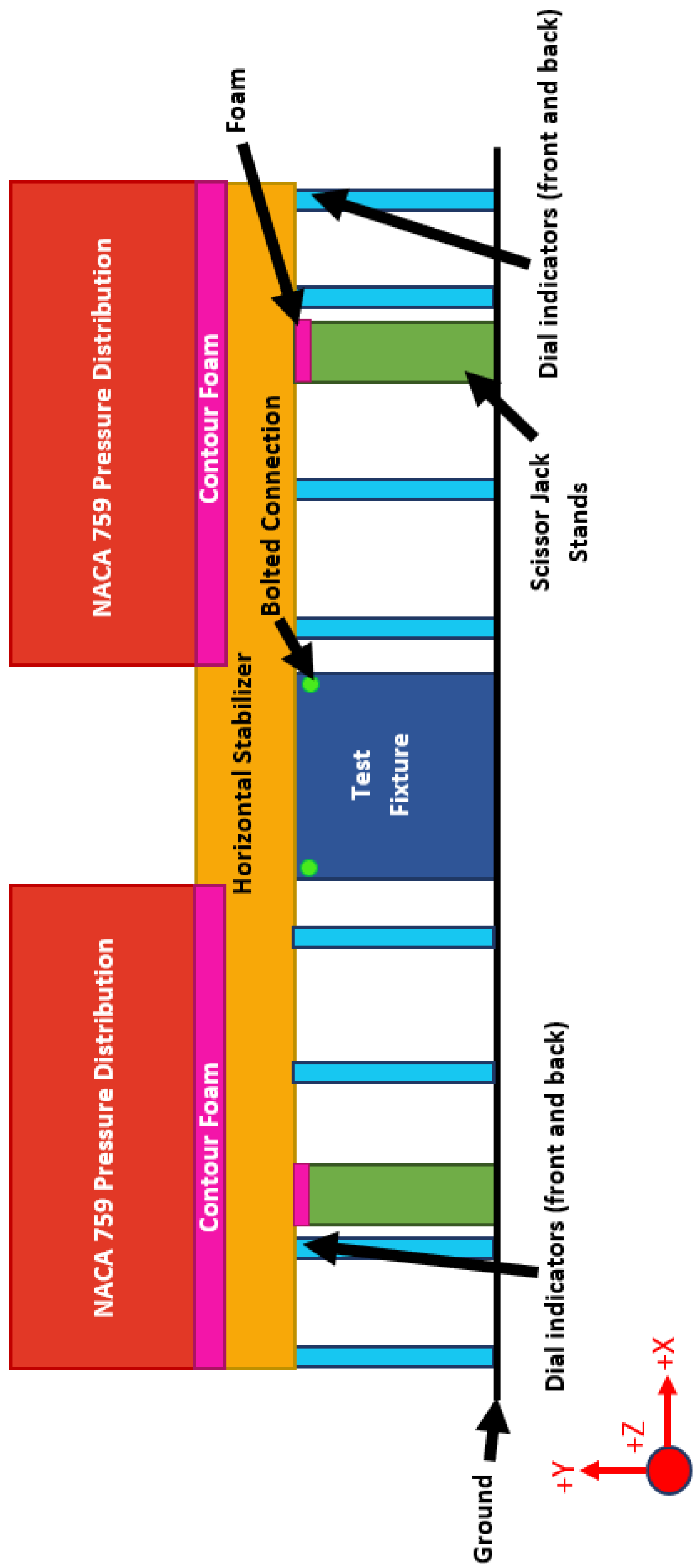


Figure 50: Mechanical Block Diagram for the chosen concept.

11. Procedure

Materials needed and Preliminary Steps

1. For the desire angle of attack, determine the amount of weight needed to add to each side of the entire HS and how much weight will be added to each element

2. Gather materials needed for the experiment
    a. Test Fixture
    b. Foam
    c. Wedges (prefabricated by the Senior Design Team)
    d. Duct Tape
    e. Nuts and Bolts
    f. Both sides of the HS
    g. Sandbags
    h. Sand
    i. Displacement gauges (set up prefabricated by Senior Design team where the gauges are attached to wooden stands to sit below the HS)
    j. Jack stands
    k. Scale
    l. Reinforcements (prefabricated by the Senior Design Team)

3. Create sandbags with the desired amount of weight needed per element (this will depend on the angle of attack)

Set-up (for loading over the shear center and quarter chord)

4. Move the Test Fixture Stand to a testing area
5. Install Reinforcements on the bottom of the Test Fixture
5. Bolt the desired Testing Plate to the Test Fixture Stand (the Senior Design Team will fabricate Testing Plates for -5 and 12 degrees)
6. Bolt the HS to the Testing Plate
7. Cryand wrap the foam to the HS

8. Place the jack stands under the HS while adding additional weight in case the HS fails, the jack stands will be there to catch it
9. Place the "dial indicators" on the marked locations under the HS's
10. Add the sandbags incrementally by each element at the same rate on both sides until the entire desired load is added (*if testing to failure, keep adding incrementally until a failure occurs)*
11. Record the displacement measured on the "dial indicators" into the Excel sheet

Disassembly

1. Remove the sandbags
2. Remove the foam from the HS
3. Remove the jack stands
4. Remove the HS from the Testing Plate
5. Remove the Wedges from the test fixture tabletop

Repeat with the other angles of attack

12. Analytical Models MATLAB Code

Horizontal Stabilizer Deflection (Transverse and Angular) code

```
clc
clear
close all
```

Inputs for both models

```
nonaerodynamicload=0; %set this equal to 1 if you are wanting to make a load that isn't
%derived from aerodynamics.  FOr aerodynamic loads, set this equal to 0;

% Aerodynamic loading inputs
T= 23.36; % air temperature 10,000 ft above sea level, F
rho= 17.56*10^(-4); %density of air at 10,000 ft, slugs/ft^3
mu= 3.534*10^(-7); %dynamic viscosity, slugs/ft-s
g=3243; %gravity, ft/s^2
v_0= 410.667; %velocity of is 280 mph, ft/s
q= rho*v_0^2/2; %slug/ft-s^2  the dynamic pressure
alpha=5*(pi/180); %angle of attack, in radians

%Stabilizer Geometry (divided into 10 sections)
total_length= 49.26; %in - Half length from root to tip of stabilizer
```

```
%Area Moment of Inertias at each section
Izz= [5.75556, 5.05579, 4.57823, 4.01221, 3.50872, 4.21095, 2.6318, 2.35151, 2.07187, 1.85405,
2.02486]; %in^4
Izzft=(Izz./(12^4)); %unit conversion to ft^4
Izy=[-0.0021 -0.00537 -0.0604 -0.00475 -0.00272 -0.00858 -0.08519 -0.28144 0.00321 -0.01636 -
0.055289];
Izy=flip(Izy);
Iyy=[34.87844 29.48296 32.78697 37.38415 41.8851 62.68034 65.58443 75.60962 8100747 99.73095
115.91292];
Iyy=flip(Iyy);
%Centroid of each section
ybar=[-0.04628 -0.0006 -0.00011 -0.01263 -0.00398 0.00019 -0.0002 -0.00037 -0.00565 -0.00049 -
0.00016]; %use value from model
ybar=flip(ybar);
zbar=[-7.84926 -7.35625 -7.24522 -6.86758 -6.5826 -5.99439 -7.21008 -6.88858 -6.52269 -6.25603 -
7.47702]; %use value from model
zbar=flip(zbar);

%Shear flow model inputs


%lengths of the stabilizer walls
L12=[12.2516 11.8273561 11.40312195 10.97887805 10.5546439 11304 9.706156096 9.281921952
8.857678048 8.433443904 8.0092]; %in
L34=L12;
L23=[3.4445 3.329818945 3.215140528 300459472 2.985781055 2.8711 2.756418945 2.641740528
2.527059472 2.412381055 2.2977];
L14=[3.0758 2.94753882 2.81928059 2.69101941 2.56276118 2.4345 2.30623882 27798059 2.04971941
1.92146118 1.7932];
L23o=[17.646 17.4718784 17.2977608 17236392 16.9495216 16.7754 16.6012784 16.4271608 16.2530392
16.0789216 15.9048];


%Boom areas (not including the skin... just the spar areas) for the
%stabilizer
B2=[0.605 0.498404502 0.391811457 0.285215959 0.178622914 0.11335 0.111299981 0.109250009
0.107199991 0.105150019 0.1031]; %in^2
B3=B2;
B1=[0.355 0.32963291 0.304266404 0.278899314 0.253532808 0.195 0.169769768 0.144540116
0.119309884 0.094080232 0.06885];
B4=B1;


%model Adjustments
zbarboom=-1.*(B2.*L12.*2./(B2.*2+B1.*2)); %to check against solidworks model
Izzboom=(2*B1.*(L14./2).^2+2.*B2.*(L23./2).^2); %to check against solidoworks model
%zbar=zbarboom;  %didn't make much difference
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Izz=Izzboom;   %makes quite a bit of difference.   The Izz from the CAD model includes
% the effects of the skin in bending, the Izz from the boom areas doesn't
% include the skin in bending.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Iyy=Iyy.*1; %doesn't matter for shear center
```

```
%Iyz=Izy.*0; %doesn't matter for shear center
%ybar=0.*ybar; %makes the qb21check equal to zero if you do this, slightly affects shear center


%thicknesses of the stabilizer members
t34=0.032; %in
t12=t34;
t23=0.04;
t14=t23;
t23o=t34;

%shear modulus of the members of the stabilizer
G34=3770000; %psi
G12=G34;
G23=G34;
G14=G34;
G23o=G34;

%Areas
AI=[22.23 21.079 19.928 18.777 17.626 16.475 15.324 1473 13.022 11.871 10.72]; %area of nose
(in^2)
AII=L12.*L23; %area of remaining box (in^2)

%Stabilizer Material Youngs modulus
E=(10*10^6)*(12^2); %in lbf/ft^2  modulus E in psi for Aluminum T-6061

%Stabilizer geometry calculations (do not change)
n=10; %number of sections stabilizer divided into
l = total_length/n; %length of each division in inches
chordlocation=linspace(0,total_length,n+1);
chordlocationft=chordlocation./12;
clength=[13.69, 14.38, 15.08, 15.77, 16.46, 175, 17.84, 18.53, 19.23, 19.92, 20.41];
clength=flip(clength);
clengthft=clength./12; %going to ft

%Place where aerodynamic load occurs (on quarter chord for this HS)
Syloc=.75*clength; %quarter chord location from rear spar
```

Aerodynamic Loading Calculations

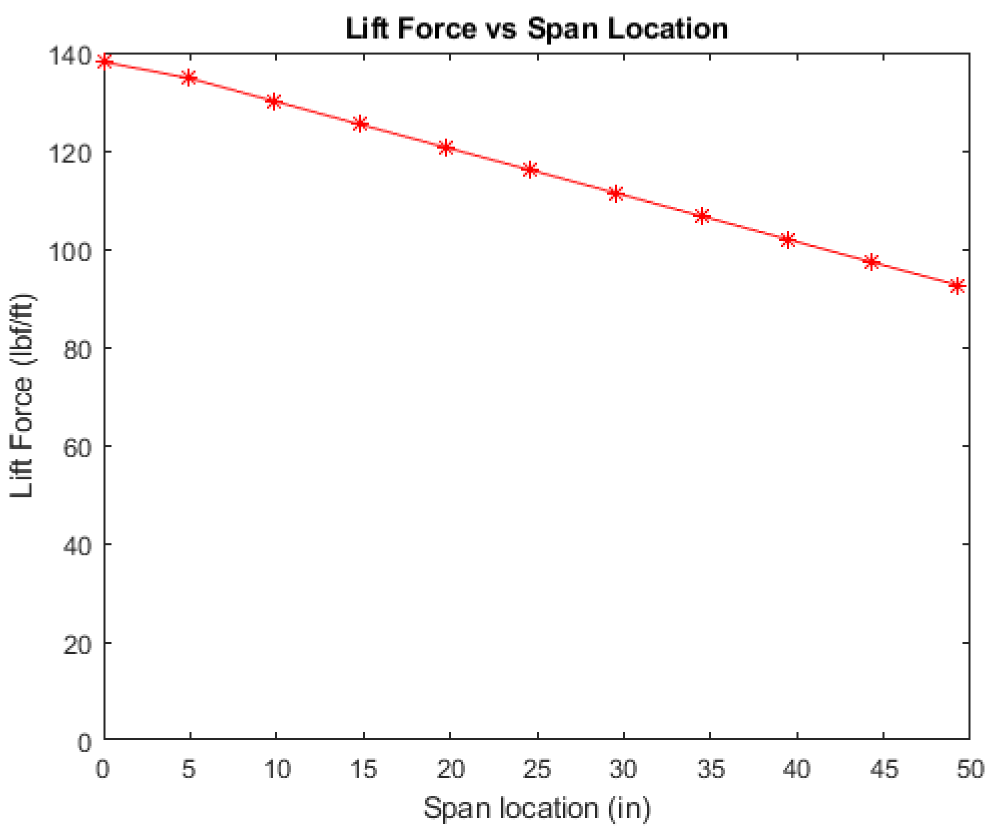
```
%Reynolds Number
Re= (rho*v_0*clengthft/mu);

% since Airfoil Tools, only give us one reynolds number for the Re's
% calculated. Our Re ranged from 2.3 - 3.5 million but airfoil tools only
% goes to Re= 1 million. The data below show the coeficients for a reynolds
% number of 1 million.

cL= 2*pi*alpha; %Lift coeffience for distribution 1
cM= 0; %Lift coeffience for distribution 1. % This comes for thin-airfoil theory

% check the units on this and the equation for moment
```

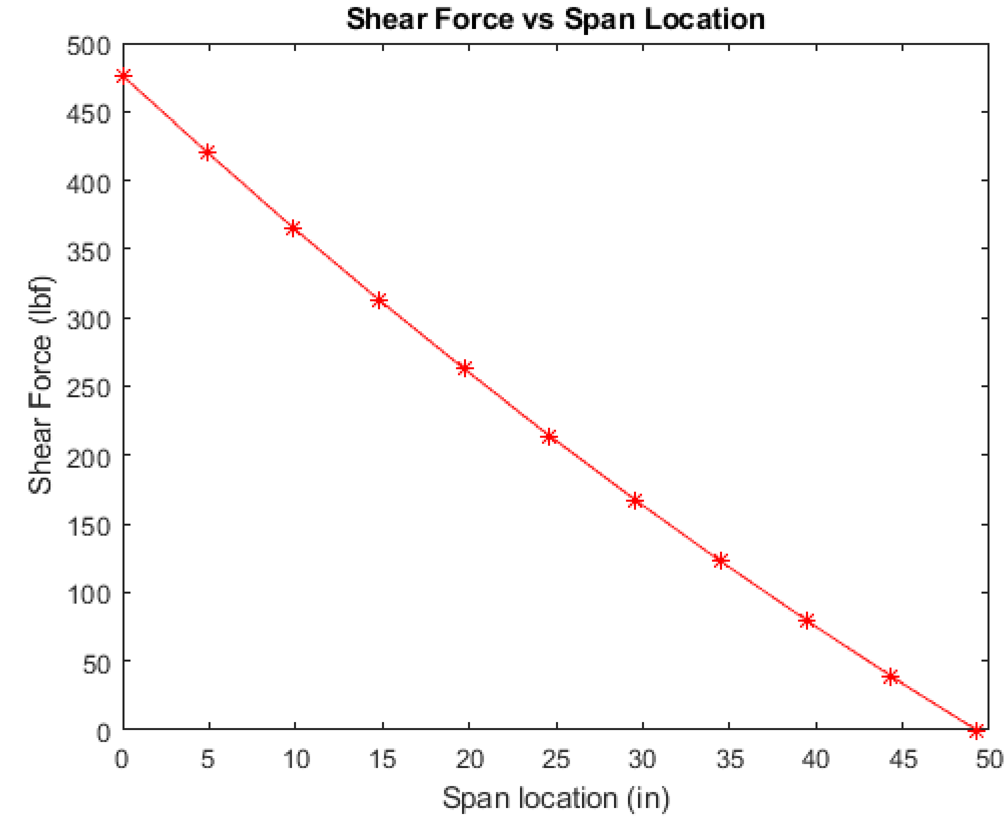
```
% pitching moment causes the wing to rotate at the quarter chord, which in
% this case it is zero because of the thin airfoil theory.
LiftForce= (cL*q*clengthft); %lbf/ft
Pitching_moment= (cM*q*clengthft.^2); %(lbf-ft)/ft


if nonaerodynamicload==1
%%%%%% for non-aerodynamic load %%%%%
LiftForce=[0,0,0,0,0,0,0,0,0,0,0]; %
end


%plotting the lift distribution and pitching moment
figure;
plot(chordlocation , LiftForce, 'r-*');
xlabel('Span location (in)');
ylabel('Lift Force (lbf/ft)');
title("Lift Force vs Span Location");
axis([0 50 0 140])


% figure;
% plot(chordlocation, Pitching_moment, 'r-*');
% xlabel('Span location (in)');
% ylabel('Moment (lbf-ft/ft)');
% title("Pitching Moment vs Span Location");
```

Integration to go from distributed load to moment

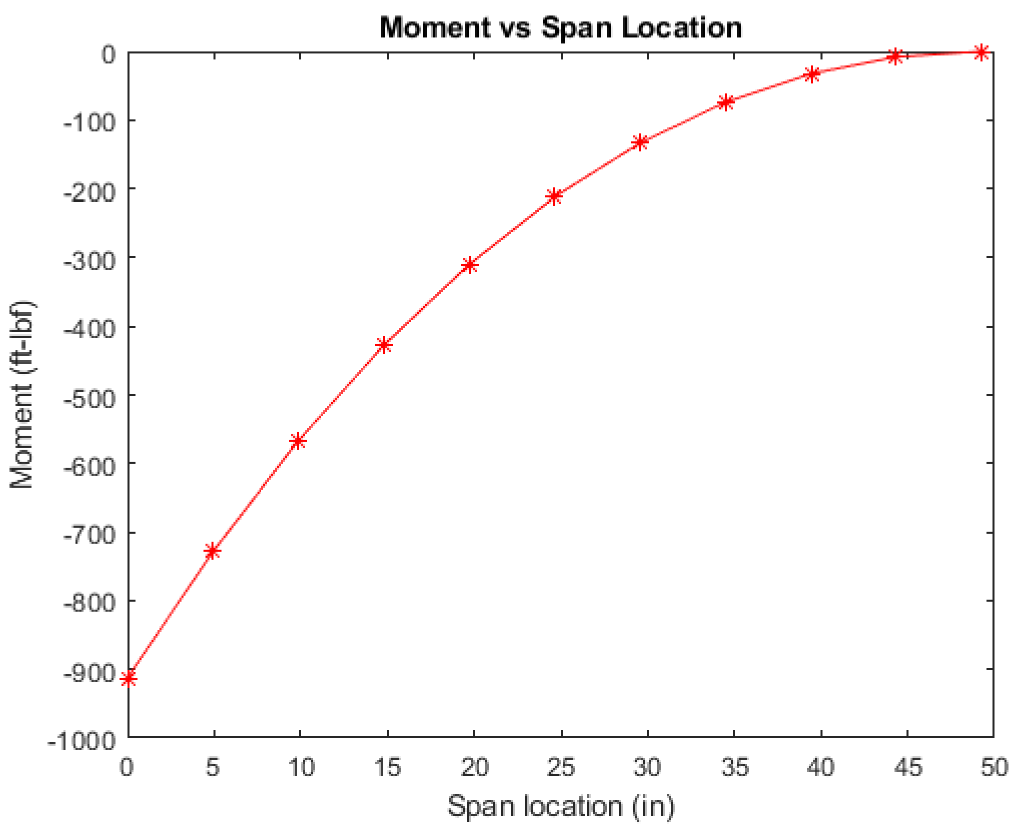
```
%Use command cumtrapz(spanlocationvector,-1*liftdistributionvector) to integrate
%numerically
shear=cumtrapz(chordlocationft, -LiftForce); %in Lbf

if nonaerodynamicload==1
%%%%%% for non-aerodynamic load %%%%%
shear=[0,0,0,0,0,0,0,0,0,-300,-300]; % %remember once shear load starts it stays on (think of
shear diagram)
end

%Find the constant of integration by realizing that at the end of the wing
%the shear should be zero.
shear=shear-shear(end); %in lbf

%Find the moment with command cumtrapz(spanlocationvector, shearvector)
%Moment that is causing the wing to bend

moment=cumtrapz(chordlocationft, shear); % in ft-lbf

%find the constant of integration by realizing the moment at the end of the
%wing must be zero.
moment=moment-moment(end); % in ft-lbf
```

```
%plotting to check
figure;
plot(chordlocation , shear, 'r-*');
xlabel('Span location (in)');
ylabel('Shear Force (lbf)');
title("Shear Force vs Span Location");

figure;
plot(chordlocation , moment, 'r-*');
xlabel('Span location (in)');
ylabel('Moment (ft-lbf)');
title("Moment vs Span Location");
```





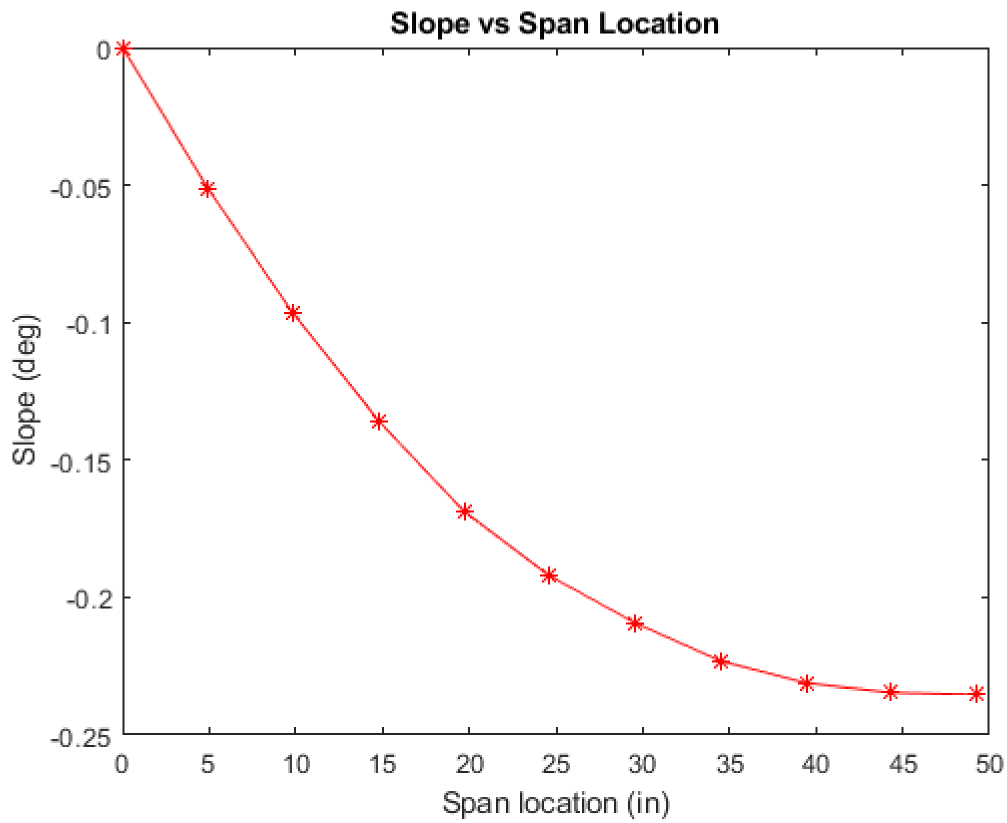
Shear Force vs Span Location
Shear Force (lbf)
500
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
30
35
40
45
50
Span location (in)

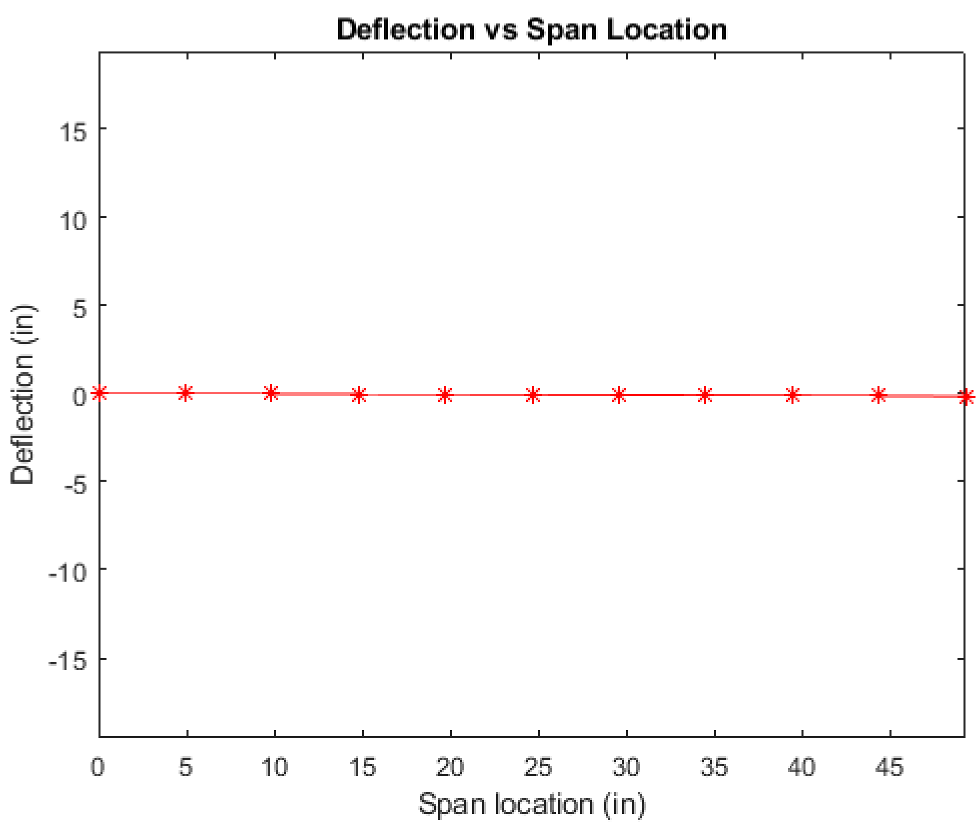


Moment vs Span Location
Moment (ft-lbf)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
0
5
10
15
20
25
30
35
40
45
50
Span location (in)

Transverse Deflection

```
%Compute the M/EI terms in a loop
for i=1:length(chordlocationft)

    MEI(i)=moment(i)/(E*Izzft(i));
end

%slope from numerical integration using cumtrapz
slope=cumtrapz(chordlocationft, MEI); %in Radians

%slope at root x=0 must be zero to solve for constant of integration.
%Cumtrapz does this.

%plot the slope
figure;
plot(chordlocation , slope.*(180/pi), 'r-*');
xlabel('Span location (in)');
ylabel('Slope (deg)');
title("Slope vs Span Location");

%deflection from numerical integration
deflection=cumtrapz(chordlocation, slope);

figure;
plot(chordlocation , deflection, 'r-*');
xlabel('Span location (in)');
ylabel('Deflection (in)');
title("Deflection vs Span Location");

axis equal
%deflection at root x=0 must be zero to get constant of integration

%total lift force
liftotal=trapz(chordlocationft, LiftForce); %this is for half the stabilizer
liftotal2=liftotal*2; %accounting for 2 sides of the HS.
```


Slope vs Span Location
Slope (deg)
0
-0.05
-0.1
-0.15
-0.2
-0.25
0 5 10 15 20 25 30 35 40 45 50
Span location (in)


Deflection vs Span Location
Deflection (in)
15
10
5
0
-5
-10
-15
0 5 10 15 20 25 30 35 40 45
Span location (in)

Shear Center Calculations

```
%needed variables
syms q_s0I q_s0II zita0

SyShearCenter=ones(1,11); %put in arbitrary load to get shear center
Sz=0; %no drag force considered, just lift
```

Step 1 Write shear modulus weighted thicknesses

Not required since we have all the same material for the stabilizer Gref=G34;

t34s=t34*G34/Gref; t12s=t12*G12/Gref; t23s=t23*G23/Gref; t36s=t36*G36/Gref;

t45s=t45*G45/Gref; t56s=t56*G56/Gref; t67s=t67*G67/Gref; t78s=t78*G78/Gref;

t81s=t81*G81/Gref;

```
% for loop to calculate each section
for i=1:11
```

Step 2 Calculate modulus thickness weighter perimeter values for each wall and cell

```
%d=integral of ds/t*
d12=L12(i)/t12;
d34=L34(i)/t34;
d23=L23(i)/t23;
d14=L14(i)/t14;
d23o=L23o(i)/t23o;


%for the loops
dI=d23+d23o;
dII=d12+d23+d34+d14;
```

Step 3 Calculate centroid and Ixx

```
%done above
```

Step 4 Calculate the bending stresses if desired

```
%forgoing here
```

Step 5 Cut cell walls 12 and 23o for each cell section

```
qb21=0;
qb23o=0;
```

Step 6 Calculate qb in each cell wall

```
%assume walls carry no direct shear so tD=0
%Second loop  (%need to figure these out where you don't cross an unknown
qb14=qb21+-((Sz*Izz(i)-SyShearCenter(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B1(i)*(-zbar(i)))-
((SyShearCenter(i)*Iyy(i)-Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B1(i)*(L14(i)/2-ybar(i)));
qb43=qb14+-((Sz*Izz(i)-SyShearCenter(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B4(i)*(-zbar(i)))-
((SyShearCenter(i)*Iyy(i)-Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B4(i)*(-L14(i)/2-ybar(i)));

qb32=qb43+qb23o+-((Sz*Izz(i)-SyShearCenter(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B3(i)*(-L34(i)-
zbar(i)))-((SyShearCenter(i)*Iyy(i)-Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B3(i)*(-L23(i)/2-
ybar(i)));
qb21check=qb32+-((Sz*Izz(i)-SyShearCenter(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B2(i)*(-L12(i)-
zbar(i)))-((SyShearCenter(i)*Iyy(i)-Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B2(i)*(L23(i)/2-
ybar(i)));
```

Step 7 Calculate the rate of twist for each cell

```
A1=AI(i);
A2=AII(i);

basicII=qb21*d12+qb14*d14+qb43*d34+qb32*d23;
basicI=qb23o*d23o+qb32*d23;

eqI=(1/(2*A1*G12))*(q_s0I*dI-q_s0II*d23+basicI); %rate of twist of cell I
eqII=(1/(2*A2*G12))*(q_s0II*dII-q_s0I*d23+basicII); %rate of twist of cell II
```

Step 8 Take moment equilibrium about point

```
%For finding the shear center this is not needed.
```

Step 9 Solve equations from step 7 and 8

```
%For the shear center this case we only needed step 7 and could set them equal to zero
%because it goes through the shear center
[q_s0i, q_s0ii]=solve(eqI,eqII,q_s0I,q_s0II);

q_s0i=double(q_s0i);
q_s0ii=double(q_s0ii);

eqIIIn=SyShearCenter(i)*zita0+qb21*L12(i)*(L14(i)/2)+qb14*L14(i)*(0)+qb43*L34(i)*(L14(i)/2)+qb32*
L23(i)*(L34(i))+2*A1*q_s0i+2*A2*q_s0ii;
```

```
[zita0solution]=solve(eqIIIn,zita0); %shear center x location from diagram in book
zita0solution=vpa(zita0solution,4);
xs(i)=double(zita0solution);
```

Step 10: Calculate the total shear flows

```
q21(i)=double(qb21+q_s0ii);
q14(i)=double(qb14+q_s0ii);
q43(i)=double(qb43+q_s0ii);
q32(i)=double(qb32+q_s0ii-q_s0i);
q23o(i)=double(qb23o+q_s0i);

end
```

For the aerodynamic load, calculate shear flows and Angular Deflection

```
% Shear center location from above (from trailing edge (coordinate system set up so negative z
direction into HS)
%either from code or experimentally

%Loading
Sy=shear;
Sz=0;

%needed variables
syms q_s0I q_s0II

% Step 1 to 5 are the same as above, so no need to repeat here

for i=1:11
```

Step 2 Calculate modulus thickness weighter perimeter values for each wall and cel

Step 3 Calculate centroid and Ixx

Step 4 Calculate the bending stresses if desired

Step 5 Cut cell walls 12 and 23o for each cell section

Step 6 Calculate qb in each cell wall

```
%assume walls carry no direct shear so tD=0
%Second loop  (%need to figure these out where you don't cross an unknown

qb21=0;
qb14=qb21+-((Sz*Izz(i)-Sy(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B1(i)*(-zbar(i)))-((Sy(i)*Iyy(i)-
Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B1(i)*(L14(i)/2-ybar(i)));
qb43=qb14+-((Sz*Izz(i)-Sy(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B4(i)*(-zbar(i)))-((Sy(i)*Iyy(i)-
Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B4(i)*(-L14(i)/2-ybar(i)));
qb23o=0;
```

```
qb32=qb43+qb23o+-((Sz*Izz(i)-Sy(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B3(i)*(-L34(i)-zbar(i)))-
((Sy(i)*Iyy(i)-Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B3(i)*(-L23(i)/2-ybar(i)));
qb21check=qb32+-((Sz*Izz(i)-Sy(i)*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B2(i)*(-L12(i)-zbar(i)))-
((Sy(i)*Iyy(i)-Sz*Izy(i))/(Izz(i)*Iyy(i)-Izy(i)^2))*(B2(i)*(L23(i)/2-ybar(i)));
```

Step 7 Calculate the rate of twist for each cell

```
A1=AI(i);
A2=AII(i);

basicII=qb21*d12+qb14*d14+qb43*d34+qb32*d23;
basicI=qb23o*d23o+qb32*d23;

eqI=(1/(2*A1*G12))*(q_s0I*dI-q_s0II*d23+basicI); %angular twist rate of cell one
eqII=(1/(2*A2*G12))*(q_s0II*dII-q_s0I*d23+basicII); %angular twist rate of cell two
```

Take moment equilibrium about point

```
eta0=0;
zita0=Syloc(i);

eqIII=Sz*eta0-Sy(i)*zita0+qb21*L12(i)*L14(i)/2+qb14*L14(i)*0+qb43*L34(i)*L14(i)/2+...
     qb32*L23(i)*L12(i)+...
     2*A1*q_s0I+2*A2*q_s0II;%let's sum moments about intersecction of z axis and 14.  CCW
positive
%left off qb23o because it is cut and goes to zero, no easy moment arm
%%%%% CCW positive except for Sy and Sx, then opposite, CW positive.
```

Step 9 Solve equations from step 7 and 8

```
%Set the rates of twist equal to each other, and then the moment sum equal
%to zero
[q_s0i, q_s0ii]=solve(eqI-eqII,eqIII,q_s0I,q_s0II);

q_s0i=double(q_s0i);
q_s0ii=double(q_s0ii);
```

Step 10: Calculate the total shear flows

```
q21(i)=double(qb21+q_s0ii);
q14(i)=double(qb14+q_s0ii);
q43(i)=double(qb43+q_s0ii);
q32(i)=double(qb32+q_s0ii-q_s0i);
q23o(i)=double(qb23o+q_s0i);
```

Calculate out the rate of twist

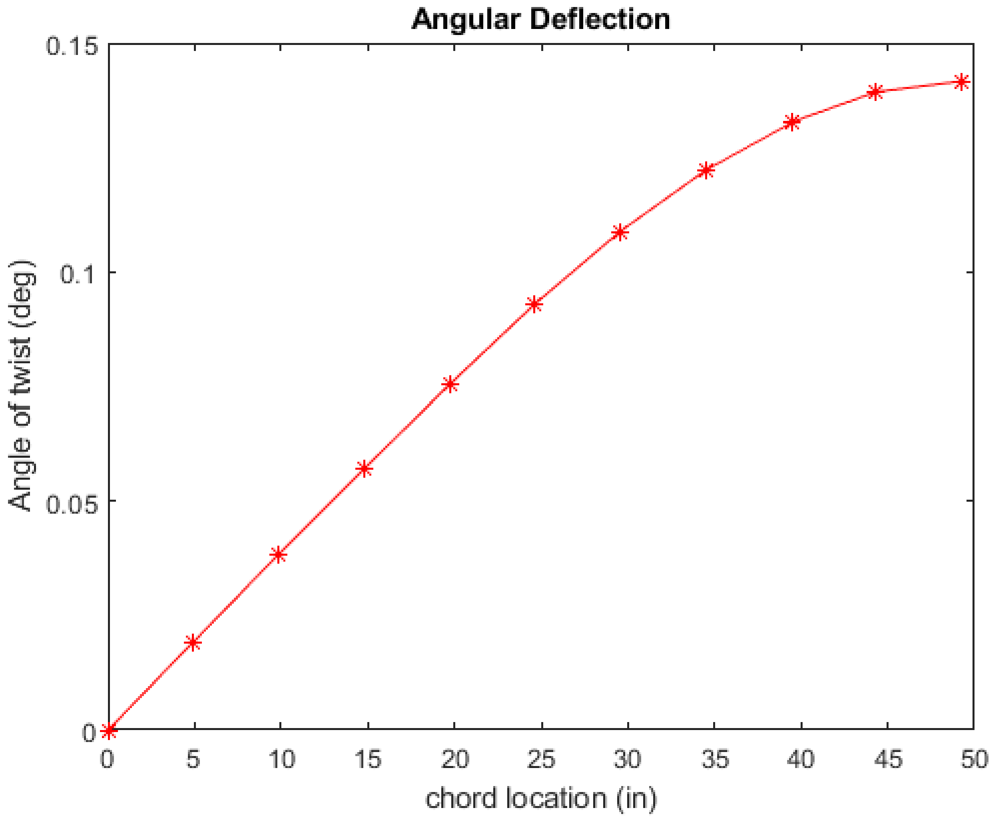
```
RateTwist1(i)=(1/(2*A1*G12))*(q_s0i*dI-q_s0ii*d23+basicI); %angular twist rate of cell one
RateTwist2(i)=(1/(2*A2*G12))*(q_s0ii*dII-q_s0i*d23+basicII); %angular twist rate of cell two
%these should both be the same

end
```

Integrating the rate of twist

```
AngleTwistRad=cumtrapz(chordlocation, RateTwist1);
%angle of twist should be zero at the root to solve for constant of
%integration
AngleTwistRad=AngleTwistRad-AngleTwistRad(1);

AngleTwistDeg=AngleTwistRad*180/pi;
```

Plot angular deflection

```
figure
plot(chordlocation,AngleTwistDeg, 'r-*');
xlabel('chord location (in)')
ylabel('Angle of twist (deg)')
title('Angular Deflection')
```



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Appendix B: ABET Outcome 2, Design Factor Considerations

ABET Outcome 2 states "*An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health safety, and welfare, as well as global, cultural, social, environmental, and economic factors.*"

ABET also requires that design projects reference appropriate professional standards, such as IEEE, ATSM, etc.

Table 13: Design Factors Considered.

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	Pg 7
Global	N/A due to the product being locally manufactured and sold.
Cultural	N/A due to the HS not having not having any cultural impacts.
Social	N/A due to no social factors that would alter the design of the text fixture of the procedure.
Environmental	N/A due to the text ixture and procedure no
Economic	Pg 23 - Used recycled lead instead
Professional Standards	Pg 7 - FAA standard