AME 563 Computational Design of Machine Components

Final Report

Linear Static Analysis, 3D Printing, and Structural Testing of a Hat-Stiffened Fuselage

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Table of Contents

1. Introduction

1.1 Background

In any aircraft, the fuselage serves as the primary backbone of the entire structure. It not only houses passengers, cargo, and internal systems, but also connects the wings, tail, and landing gear into one integrated body. Because of this central role, the fuselage experiences a wide range of loads throughout a flight—bending during turbulence, compression during landing, torsion from aerodynamic moments, and even localized stresses from pressurization cycles. Although the outer skin appears smooth and thin, it must safely withstand all these forces without deforming or buckling. [4][5]

To meet these demands while keeping the aircraft as light as possible, engineers rely on internal stiffeners that reinforce the skin from within. These stiffeners transform the fuselage from a simple shell into a more efficient load-carrying structure, helping it resist buckling, distribute loads evenly, and maintain its shape under high stress. For designers, the challenge lies in finding a stiffener geometry that offers strong mechanical performance while remaining lightweight and practical to manufacture. In this project, we focus on understanding how different stiffener designs influence the behavior of a fuselage section, and we evaluate this through a combination of CAD modeling, finite element analysis, 3D printing, and physical testing. [5]

1.2 Project Objective

The main objective of this project is to design and evaluate a fuselage section reinforced with hat-type stiffeners and determine how effectively this configuration can carry compressive loads. Instead of treating the fuselage as a simple hollow cylinder, the project aims to study how internal stiffening elements influence its strength, deformation pattern, and overall structural efficiency. By doing this, we gain a clearer understanding of why certain stiffener geometries are preferred in the aerospace industry and how small design changes can impact performance.

To achieve this, the project combines computational analysis, additive manufacturing, and physical testing. The first step involves creating different design variations of a stiffened fuselage using CAD software. These designs are then analyzed using linear static finite element simulations to predict displacement, stress distribution, and potential weak points when subjected to compressive loads ranging from 30 lbs to 100 lbs. Once the simulations identify the most promising design, the structure is 3D-printed so that its real-world performance can be tested in a controlled environment. The final goal is to compare the numerical results with the physical test outcome, understand any differences, and draw conclusions about the validity of the design and the effectiveness of hat stiffeners.

Along with evaluating structural behavior, the project also focuses on the practicality of manufacturing the design using 3D printing. Factors such as print orientation, assembly strategy, material limitations, and weight restrictions are considered, as these play a major role in the success of the final structure. By the end of the project, the team aims to have a well-supported explanation of how hat stiffeners contribute to the strength of a fuselage and why this configuration is a suitable choice for components that must be both lightweight and structurally reliable.

1.3 Problem Statement

Designing a fuselage section that can safely withstand compressive loads without excessive deformation or premature buckling is a central challenge in aircraft structural engineering. Thin-walled cylindrical shells, while efficient in terms of weight, are inherently vulnerable to local buckling and loss of stiffness when exposed to axial compression. Without proper reinforcement, these structures can deform unpredictably, concentrate stresses at weak locations, and ultimately fail under relatively low loads. This makes the selection and design of internal stiffeners a critical part of the overall structural integrity.

The specific problem addressed in this project is to determine whether a hat-stiffened fuselage section can meet the load-bearing requirements typically expected in small-scale aerospace structures, and how its performance compares across different design variations. The project aims to identify a stiffener geometry that provides the necessary rigidity while remaining lightweight and suitable for additive manufacturing. The challenge also extends to ensuring that the design complies with practical constraints such as printability, segment assembly, and manufacturability using FDM 3D printers.

To solve this problem, the fuselage must be analyzed under controlled compressive loads ranging from 30 lbs to 100 lbs and evaluated for displacement, stress distribution, and potential failure zones. The project must bridge the gap between theoretical predictions from finite element simulations and real-world performance measured through physical testing of the 3D-printed model. Ultimately, the goal is to confirm whether the chosen stiffener configuration provides consistent and reliable structural behavior and whether it can pass the required compressive strength criteria.

2. Fuselage Structure Overview

2.1 Fuselage Description

The fuselage is the central structural body of an aircraft and serves as the primary support framework that connects all major components of the vehicle. It provides the enclosed space needed to carry passengers, cargo, fuel, avionics, and various mechanical systems, while also acting as the main attachment point for the wings, tail assembly, and landing gear. Because it must perform both structural and functional roles, the fuselage is engineered to be lightweight yet strong enough to resist a wide range of forces encountered during flight and ground operations.

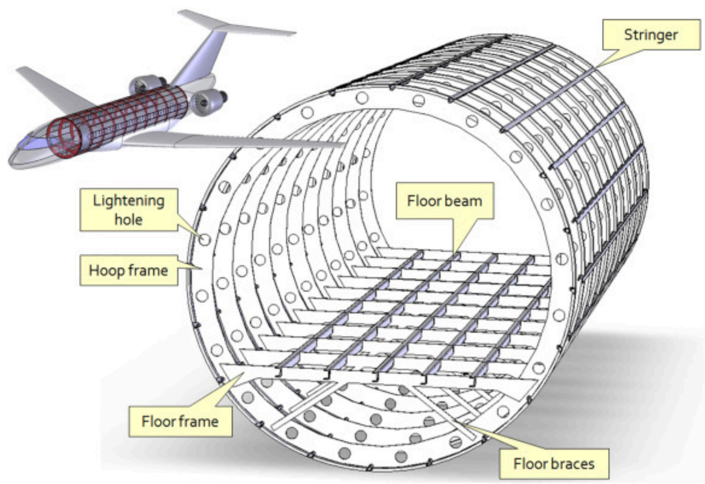


Figure 1: Fuselage cross-section [2]

Structurally, the fuselage behaves as a long, thin-walled cylindrical shell, which is efficient in distributing loads but also sensitive to issues such as local buckling, ovalization, and deformation under compression or bending. During flight, the fuselage experiences aerodynamic forces, internal pressurization cycles, bending from wing lift, and torsional loads generated by maneuvers. On the ground, it must withstand landing impacts and handling loads. As a result, even though the fuselage skin appears thin, it plays a critical role in maintaining the overall stability and safety of the aircraft.

To enhance its strength and prevent structural failures, the fuselage is reinforced with internal stiffeners, frames, and longerons that work together to support the outer skin. These reinforcements help distribute loads more evenly and ensure that the fuselage can retain its shape and structural integrity under demanding conditions. Understanding how these stiffening elements contribute to performance is essential for designing efficient aerospace structures, which is a key focus of this project.

2.2 Importance of Stiffeners in Fuselage Design

Although the fuselage skin appears simple from the outside, it functions as a highly stressed structural shell that must endure a combination of axial compression, bending loads, internal pressurization, shear forces, and torsion throughout the aircraft's operation. A thin cylindrical shell on its own is extremely prone to local buckling and deformation, especially under compressive loads. Even relatively small axial forces can cause the shell to wrinkle or collapse if it is not adequately reinforced. This is where stiffeners become essential.

Stiffeners are structural elements integrated into the fuselage to provide additional rigidity and support to the thin outer skin. They help the fuselage maintain its shape, prevent premature buckling, and improve its overall load-carrying capability. By increasing the moment of inertia and distributing stress more evenly across the structure, stiffeners allow the fuselage to withstand higher loads without adding excessive weight. This balance between strength and lightness is especially critical in aerospace applications, where every gram matters.

In addition to improving structural performance, stiffeners also contribute to the manufacturability and durability of the fuselage. They help control deformation during assembly, reduce the likelihood of cracks forming due to cyclic loads, and ensure that the aircraft retains its aerodynamic shape over time. The selection of stiffener geometry whether L-shaped, Z-shaped, T-shaped, or hat-shaped directly affects how effectively these goals are achieved. Each geometry offers its own advantages in terms of buckling resistance, load distribution, ease of fabrication, and compatibility with materials like aluminum, composites, or 3D-printed polymers.

For this project, understanding the role of stiffeners is crucial, as the primary aim is to evaluate how different stiffener designs influence the strength and deformation behavior of a fuselage section. By analyzing and testing these stiffener configurations, we gain insight into why certain geometries are preferred in real aircraft and how they can be adapted for additive manufacturing.

3. Types of Stiffeners

Different stiffener geometries offer different mechanical advantages. Some shapes are easier to manufacture, while others provide superior resistance to local buckling or higher bending rigidity. Selecting the appropriate stiffener shape depends on factors such as the expected loading conditions, available manufacturing methods, material choice, and desired weight efficiency.

In aerospace structures, four stiffener shapes are commonly used: L-stiffeners, Z-stiffeners, T-stiffeners, and hat-stiffeners. Each geometry provides a unique combination of strength, weight efficiency, and practical manufacturability. In this project, understanding the characteristics of these stiffener types is essential for determining why the hat stiffener is ultimately chosen for the fuselage design.

3.1 L-Stiffeners

L-stiffeners, also known as angle stiffeners, are one of the simplest and most widely used stiffener shapes in structural applications. They consist of two flat legs joined at a right angle, forming an "L" profile. Because of their simplicity, L-stiffeners are easy to manufacture, lightweight, and straightforward to attach to structural skins or panels.

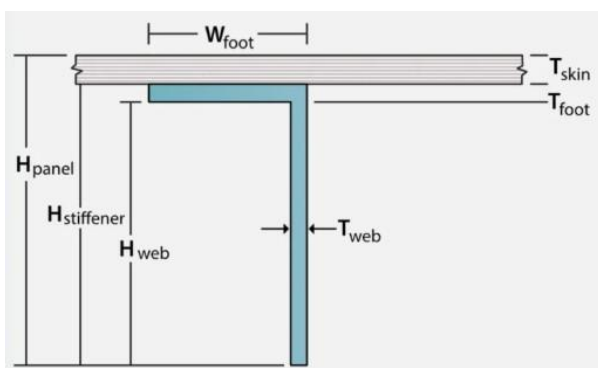


Figure 2: L-Shaped stiffener [3]

In terms of mechanical behavior, L-stiffeners provide moderate improvement in bending stiffness and help delay the onset of local buckling, particularly along thin plates. However, their open-section geometry makes them less effective in resisting torsional loads or large compressive forces compared to closed-section stiffeners. Under high loads, L-stiffeners can twist or rotate, reducing their reinforcement effectiveness.

Despite these limitations, L-stiffeners are commonly used in areas where load demands are moderate or where manufacturing simplicity is a priority. They serve as a useful baseline for comparison when evaluating more advanced stiffener geometries, such as Z-, T-, or hat stiffeners, which offer improved performance for aerospace structures.

3.2 Z-Stiffeners

Z-stiffeners have a cross-section shaped like the letter "Z," consisting of two flanges connected by a central web. This geometry creates an efficient load path that allows the stiffener to support both compressive and shear stresses without excessive twisting or rotation. Compared to simple L-stiffeners, the Z-shape offers better stability because the flanges extend in opposite directions, providing a more balanced structural response under loading.

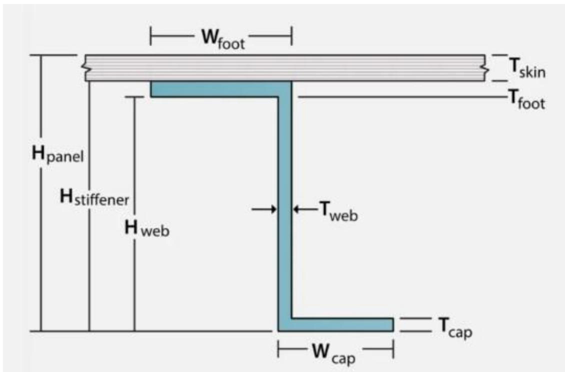


Figure 3: Z-Shaped stiffener [3]

One of the key advantages of Z-stiffeners is their improved ability to resist local buckling, especially when attached to thin skins or panels. The opposite-facing flanges help clamp the skin more effectively, allowing the stiffener to distribute loads over a wider area. This makes Z-stiffeners a popular choice in aircraft fuselage panels, wing structures, and composite components where weight reduction and stiffness are critical.

However, Z-stiffeners can be more challenging to manufacture, especially when using materials that require precise forming or bonding. In additive manufacturing applications, printing a Z-profile can also introduce support material or orientation issues depending on the printer setup. Despite these challenges, Z-stiffeners remain an efficient option for many aerospace structures because they offer a strong balance between weight, performance, and structural reliability.

3.3 T-Stiffeners

T-stiffeners have a cross-sectional shape resembling the letter “T,” consisting of a vertical web and a horizontal flange. This configuration provides a strong increase in bending stiffness, especially in the direction perpendicular to the web. Because of their geometry, T-stiffeners are commonly used in applications where the structure must resist significant compressive loads along a single primary axis.

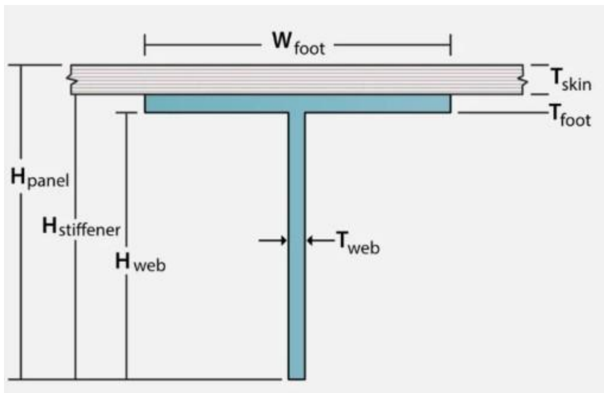


Figure 4: T-Shaped stiffener [3]

The vertical web of a T-stiffener carries most of the compressive force, while the flange helps spread the load across the skin and reduces the likelihood of local buckling. This makes T-stiffeners particularly effective in reinforcing long, flat panels or regions that experience heavy axial compression. The relatively large moment of inertia created by the T-profile gives the stiffener a high strength-to-weight ratio in the intended loading direction.

Despite these advantages, T-stiffeners also have some drawbacks. The open-section shape makes them more vulnerable to torsional deformation compared to closed-section stiffeners, meaning they may twist or rotate under combined loading. Manufacturing can also be more complex, as the flange-to-skin interface may require precise bonding or fastening. In the context of 3D printing, T-stiffeners may demand additional support structures or careful part orientation to avoid warping during fabrication.

Overall, T-stiffeners offer strong directional stiffness, but their open geometry and manufacturing requirements can limit their effectiveness in situations where multidirectional loads or buckling stability are primary concerns. This makes them useful for comparison but not always the best choice for lightweight fuselage reinforcement.

3.4 Hat-Stiffeners

Hat-stiffeners, often called top-hat stiffeners, feature a closed or semi-closed cross-section consisting of a central crown, two vertical webs, and outward-extending flanges. This geometric shape gives them a deeper structural profile compared to open stiffeners, which directly enhances their ability to resist bending and buckling loads. Because the hat section behaves more like a closed tube, it offers high stiffness with minimal added weight, making it especially useful in lightweight aerospace structures.

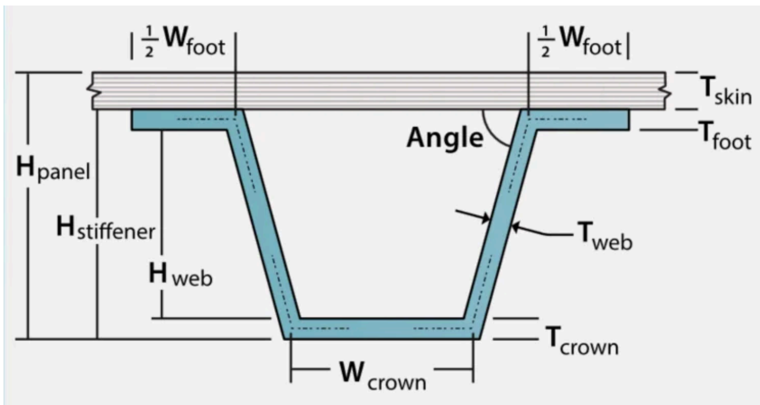


Figure 5: Hat-Shaped stiffener [3]

The deeper cross-section increases the moment of inertia, which significantly improves resistance to compressive buckling—one of the most common failure modes in thin-walled fuselage skins. Unlike L, Z, or T profiles, the hat stiffener does not twist easily under load because both webs support the shape symmetrically. This reduces torsional deformation and helps the stiffener maintain its structural alignment even when subjected to complex loading conditions.

Another important benefit is the way hat-stiffeners distribute loads into the fuselage skin. The wide flange surface provides a more stable interface for attachment, allowing load transfer over a larger area and reducing stress concentrations at critical points. This results in a more uniform stress distribution around the fuselage and contributes to improved overall structural performance.

Hat-stiffeners are also practical from a manufacturing standpoint. Their geometry is well-suited for additive manufacturing because the section provides good stability during printing, minimizing distortion or sagging. The shape can often be printed without excessive support material, which reduces post-processing effort. The design can also be printed as a single integrated piece, eliminating the need for additional adhesive joints or mechanical fasteners.

In summary, hat-stiffeners combine the advantages of high bending rigidity, excellent buckling resistance, torsional stability, and manufacturing convenience, making them a strong candidate for high-performance fuselage reinforcement.

3.5 Reason for Selecting Hat Stiffeners

The decision to use hat-stiffeners in this project is based on a combination of structural performance, manufacturing practicality, and alignment with the project's overall goals. Several factors make hat-stiffeners the most suitable choice compared to alternative stiffener types:

Superior Buckling Resistance

The closed-section geometry of the hat stiffener significantly delays buckling under axial compression. Because this project focuses on compressive load testing (30–100 lbs), a stiffener with strong buckling resistance is essential for maintaining structural integrity.

High Bending Rigidity

The deeper profile created by the crown and vertical webs increases the bending stiffness of the fuselage section. This allows the structure to resist deformation more effectively, which is critical for preventing failure during compressive load tests.

Improved Load Distribution

The wide flanges of a hat stiffener distribute loads more evenly across the fuselage skin. This reduces stress concentrations and helps prevent localized deformation or cracking around attachment points.

Stability Under Multi-Directional Loads

Unlike L or T stiffeners, which can rotate or twist, hat stiffeners offer better torsional stability. This stability is particularly valuable in cylindrical fuselage designs where load directions can vary due to geometry.

Additive Manufacturing Compatibility

Hat-stiffeners are easier to 3D print because their shape is more stable during fabrication. The broad base and symmetrical walls reduce warping, while the closed section allows the stiffener to be printed as a single, continuous component.

Weight Efficiency

Even with superior stiffness, hat-stiffeners maintain a favorable strength-to-weight ratio. For this project, where both weight and performance are important, this makes the hat section an optimal choice.

Proven Use in Aerospace Structures

Hat-stiffeners are commonly used in aircraft fuselage and wing structures, which provides confidence that the design approach aligns with real-world engineering practices.

4. Fuselage Design Development

The fuselage design for this project was developed through an incremental and practical engineering approach. The focus was on creating a lightweight cylindrical shell reinforced internally with hat stiffeners to improve load-carrying capability. Multiple design variations were created and refined to balance strength, manufacturability, and assembly feasibility. Each version was evaluated for structural performance through simulation before selecting the most suitable stiffener for physical testing.

4.1 CAD Modeling Approach

The CAD modeling process began by defining the basic cylindrical geometry of the fuselage based on the required diameter and section height. Once the outer shell was established, the hat stiffeners were modeled as internal reinforcement features using a parametric sketch-and-extrude method, allowing quick adjustments to their width, height, and flange dimensions. The stiffeners were placed symmetrically inside the fuselage to ensure even load distribution during compression.

To make the design suitable for 3D printing, the fuselage was divided into smaller modular sections that could fit within standard printer build volumes. These sections were designed with interlocking or alignment features to ensure that the assembled structure maintains structural continuity. Smooth transitions, fillets, and consistent wall thicknesses were used to avoid sharp stress concentrations and to ensure that the model would mesh cleanly for FEA. Throughout the CAD process, attention was given to both structural requirements and practical manufacturing constraints, resulting in a design that could be analyzed, printed, and tested effectively.

4.2 Fuselage Dimensions

Across this project, three different fuselage designs were developed, each with its own set of dimensions to study how geometric variations influence structural performance. While the overall assembled fuselage length was approximately 34 inches, the height of the individual sections varied slightly between the three models based on the stiffener layout and connector features. Likewise, the diameter was not constant across the designs; each version used a different value to understand how curvature affects stiffness, buckling behavior, and load distribution.

For each design, the wall thickness, stiffener spacing, and internal reinforcement geometry were kept consistent so that meaningful comparisons could be made between the models. The hat stiffener dimensions were scaled appropriately to match the local fuselage curvature, ensuring proper contact with the inner surface and reliable load transfer during compression. These dimensional differences formed an important part of the design study, allowing us to evaluate how even small geometric changes can influence displacement, stress levels, and overall stability under loading.

4.3 Stiffener Design

The stiffener used in all three fuselage designs is a hat-shaped profile, and its geometry is defined by the dimensional layout shown in the figure below.[6] The actual dimensions relevant to the stiffener design are W1, W2, h, L, and t, which collectively describe the width of the crown, the overall base width, the stiffener height, the flange length, and the material thickness.

The crown width (W1) forms the top flat section of the stiffener and plays an important role in resisting compressive loads by providing a stable load-bearing surface. The base width (W2) determines how widely the stiffener spreads across the fuselage skin, which directly influences load distribution and buckling resistance. The height (h) controls the moment of inertia of the stiffener; increasing this height generally improves bending stiffness but also adds weight. The flange length (L) ensures that the stiffener transitions smoothly into the fuselage skin, reducing stress concentrations at the attachment points. Finally, the thickness (t) is kept consistent with the fuselage shell to maintain uniform printing and structural behavior.

Across the three fuselage variations, the same fundamental stiffener shape was retained, but the actual values of W1, W2, and h were adjusted to match the changing fuselage diameters. This ensured that the stiffener seated properly against the inner surface and provided continuous reinforcement along the length of each section. By scaling the stiffener dimensions appropriately, the design maintained a balance between stiffness, printability, and weight—allowing each version to be evaluated fairly during FEA and physical testing.

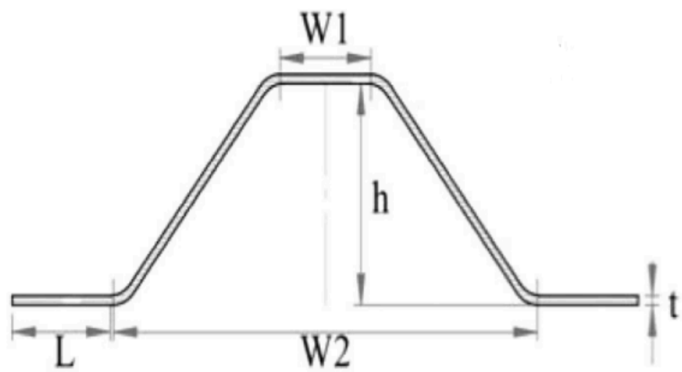


Fig 6. Hat stiffener with dimensions: W_1, W_2, L & t

4.4 Final Assembly Layout

The fuselage was divided into multiple segments to make the design compatible with standard 3D printer build volumes. Each segment includes both the cylindrical shell and its corresponding hat stiffener, allowing the full structure to behave like a continuous fuselage once assembled as shown in the figure below.[11] To ensure proper alignment, simple connector features were added at the ends of each section so that the stiffeners and shell line up accurately when joined. This modular approach made printing and handling easier while still maintaining the structural continuity required for testing.

5. Linear Static FEA Analysis

Linear static FEA analysis is used to evaluate how a structure deforms and carries load under steady, non-dynamic conditions. In this method, the fuselage model is divided into small finite elements, and the software calculates how each element responds to the applied compressive load. This approach helps identify displacement patterns, stress concentrations, and overall stiffness early in the design stage, allowing us to refine the geometry before moving to 3D printing and physical testing.

5.1 Analysis Workflow

The analysis began with creating the fuselage with hat stiffeners geometry in the NX CAD environment, where each smaller fuselage section was modeled individually and then assembled together with the connecting rods or pins to form the full 34-inch structure. Once the complete assembly was prepared, the model was transferred into the NX Nastran simulation module for meshing and analysis.

A 3D mesh was generated for each fuselage segment, ensuring that the element size was fine enough to capture the curvature of the shell and the details of the hat stiffeners. Mesh mating conditions were applied at the interfaces between segments so the full-length fuselage behaved as one continuous structure during loading. After meshing, boundary & loading conditions were applied. The model was then solved using NX Nastran under linear static conditions to evaluate displacement, stress distribution, and overall structural response.

5.2 Material Properties

PLA was selected as the material for both the simulation and 3D printing because it provides a good balance of stiffness, strength, and printability for structural prototypes. It is widely used in FDM printing due to its low warping tendency and consistent dimensional accuracy, making it suitable for producing long fuselage sections that must align precisely during assembly.

For the analysis, PLA was modeled using typical material properties obtained from standard datasheets. The material has an elastic modulus in the range of 2.5–3.5 GPa, a Poisson’s ratio of approximately 0.35, and a tensile strength of about 50–60 MPa. Its density is around 1.24 g/cm^3, which helps keep the overall structure lightweight while still offering enough rigidity for compression testing. These properties allowed the simulation to realistically capture how the printed fuselage would behave under loading and ensured that the results closely matched the expected physical performance.

Property	PLA Material	ABS Material	ASA Material
Elastic Modulus	~2.5–3.5 GPa	~1.8–2.2 GPa	~1.7–2.1 GPa
Tensile Strength	~50–60 MPa	~30–40 MPa	~30–45 MPa
Density	~1.24 g/cm³	~1.04 g/cm³	~1.07 g/cm³
Printability	Very easy, minimal warping	Moderate, prone to warping	Moderate, requires controlled temps

Table.1 Comparison of different materials.

5.2.1 Selection of Material

PLA was chosen mainly because of its excellent printability and dimensional stability, which are critical when assembling multiple fuselage sections into a 34-inch structure. ABS and ASA, although tougher, tend to warp and shrink during printing, which could lead to alignment issues when joining the segments. PLA provides higher stiffness and strength per unit weight, allowing the fuselage to maintain its shape during compression testing. Its predictable mechanical behavior also makes it easier to model accurately in NX Nastran, improving the reliability of the simulation results.

5.3 Boundary & Loading Conditions

The boundary and loading conditions were applied to replicate the actual compression testing setup, as shown in the figure below. These conditions ensure that the simulation accurately reflects how the fuselage behaves under axial loading.

Boundary Conditions:

- The bottom face of the fuselage assembly was fully constrained (all degrees of freedom fixed).
- This represents the stationary platen during physical compression testing.

Loading Conditions:

- A vertical compressive load was applied uniformly on the top surface of the fuselage.
- The load direction was strictly downward to simulate the applied force during testing.

This setup allowed the analysis to capture realistic displacement patterns, stress concentrations, and overall structural response under compression.

5.4 Model Variation - 01

Model-01 represents the first complete fuselage configuration developed for this project. The design consists of two different types of fuselage sections that work together to form the full assembly as shown in the below images [8, 9,]. The one-way fuselage section is used at the top and bottom of the structure, while the two-way fuselage section is used in the intermediate levels. The one-way section has holes only on the top surface, whereas the two-way section includes holes on both the top and bottom surfaces. This difference allows the sections to connect vertically using a connecting rod, which is placed symmetrically between segments to maintain alignment and ensure structural continuity. The two section types, along with the connecting rods, create a stable 34-inch fuselage assembly capable of transmitting compressive loads evenly across all printed parts.

Geometry

The main dimensions used for Model-01 are:

Parameter	Value
Stiffener width	6 inches
Fuselage height (single section)	5.9 inches
Diameter of fuselage	2.7 inches

Table.2 Dimensions of the Fuselage geometry - 01.

The geometry includes an internal hat stiffener running along the inside surface of each section, providing reinforcement against buckling. The connecting rod fits precisely into the holes of the fuselage sections to maintain alignment and allow the load to be transmitted through the entire height of the structure. Images of the one-way and two-way fuselage designs are shown below.

Stiffener dimensions

The key dimensions taken from the sketch are:

Parameter	Value
Crown Width (W_1)	6 inches
Base width (W_2)	W_1 * 2 = 12 inch
Stiffener height (h	**W_1** = 6 inch
Thickness (t)	same as fuselage thickness

Table.3 Dimensions of the stiffener design - 01.

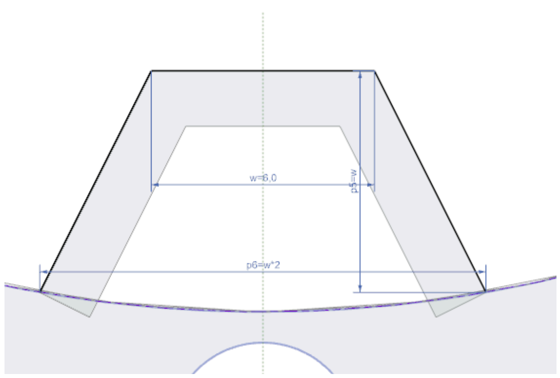


Fig 7. Stiffener dimensions

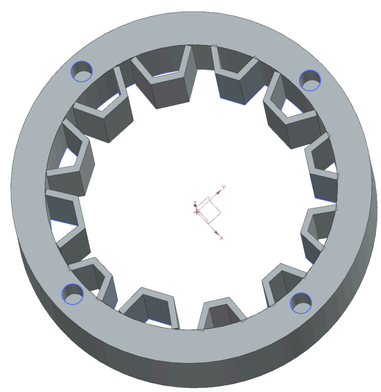


Fig 8. One way fuselage section

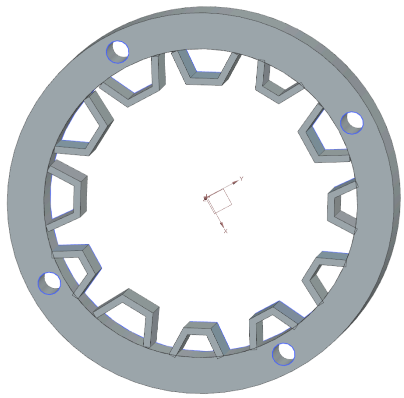


Fig 9. Two way fuselage section

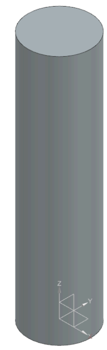


Fig 10. Connecting Rod

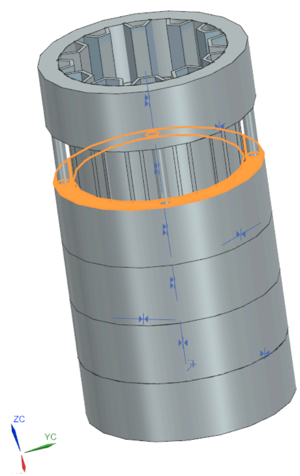


Fig 11. Fuselage Sections Assembly

Mesh details

A 3D mesh was generated for the full assembly in NX Nastran. Each fuselage section was meshed individually, and mesh mating conditions were applied at the interfaces to ensure that the sections behaved as a single continuous body under loading.

Key mesh properties:

- **Element type:** 3D tetrahedral elements
- **Mesh density:** 5 mm element size
- **Mesh connections:** Tied between one-way and two-way sections through rod interfaces

This meshing approach allowed the analysis to capture local effects around stiffeners as well as global deformation over the entire 34-inch height.

Results (displacement & stress)
The table below summarizes the displacement and stress values obtained from linear static analysis:

Load (lbf)	Displacement (mm)	Avg Von-Mises stress (MPa)	Un avg Von-Mises stress (MPa)
30	0.0189	0.657	0.626
40	0.0252	0.876	0.834
50	0.0315	1.096	1.043
60	0.0377	1.315	1.252
70	0.044	1.534	1.46
80	0.0503	1.753	1.669
90	0.0566	1.972	1.877
100	0.0629	2.191	2.086

Table.4 FEA Simulation data of fuselage with stiffener geometry design - 01.

The displacement contour in figure [12] illustrates how the fuselage deforms gradually from the fixed base toward the loaded top section. Maximum displacement occurs at the lower surface, confirming that the structure responds linearly and symmetrically under axial loading.

The image[13] shows localized stress concentrations forming along the stiffener line when the fuselage is subjected to compression. The green-to-yellow regions indicate higher stress zones where the structure experiences the greatest load transfer through the stiffener.

This plot [14] shows the displacement increasing steadily with load, indicating a clear linear relationship between applied force and deformation. The smooth upward trend confirms that the fuselage maintains structural stability throughout the loading range.

The stress variation graph [15] compares averaged and un-averaged von Mises stress values across different loads, both showing a consistent linear rise. This demonstrates that the structure behaves elastically under all applied loads, with no abrupt jumps or instability.

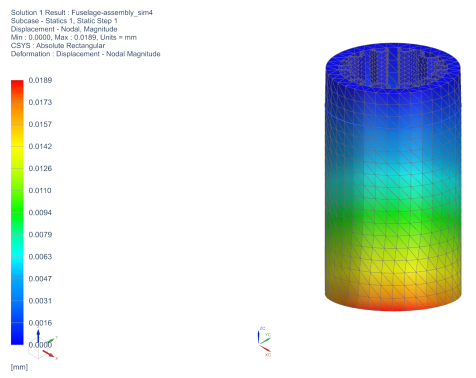


Fig 12. Displacement contour

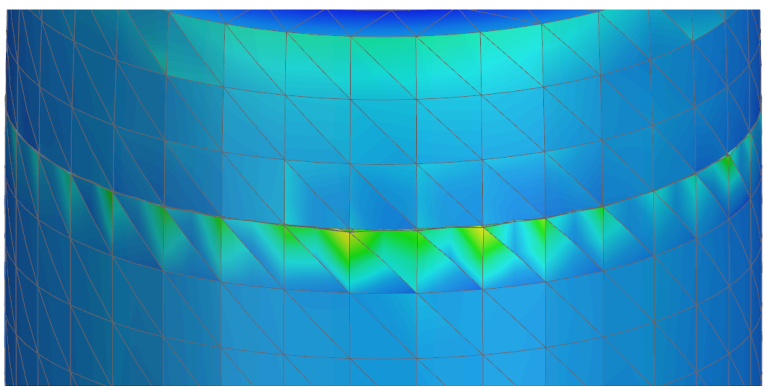
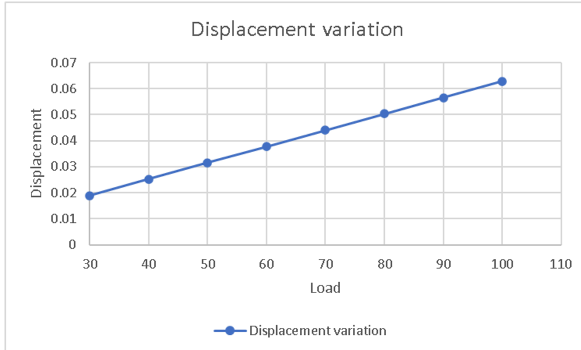


Fig 13. Peak stress region around stiffener joint



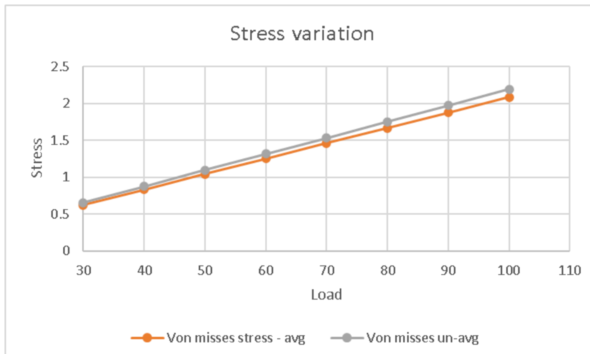


Fig 14. Displacement variation across loads *Fig 15. Stress variation across loads*

5.5 Model Variation - 02

The fuselage section in variation 2 is a cylindrical structural shell designed to represent a simplified aircraft body segment, featuring a smooth outer surface and an internally reinforced geometry. Inside the fuselage, a series of hat-shaped stiffeners are evenly distributed along the inner circumference, providing increased rigidity, buckling resistance, and improved load-carrying capability under axial and circumferential stresses. These hat stiffeners interlock with the fuselage wall through their flanged profiles, ensuring efficient transfer of aerodynamic and structural loads throughout the shell. The red part highlights the assembly pins, which act as alignment and positioning components during the manufacturing or joining process, ensuring that the stiffeners and fuselage are properly oriented before final fastening. These pins help maintain geometric accuracy, reduce assembly errors, and ensure consistent spacing between internal components. Collectively, the fuselage shell, hat stiffeners, and alignment pins create a robust and precisely assembled structural module suitable for aerospace applications or mechanical design simulations.

Geometry

The main dimensions used for Model-02 are:

- Stiffener Length: 5.66 inches
- Fuselage Length (single section): 5.66 inches
- Diameter of fuselage: 2.1 inches

Fig 16. Isometric view of fuselage design - 02

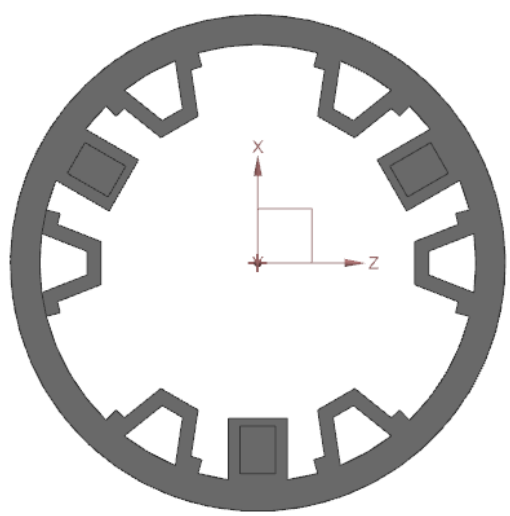
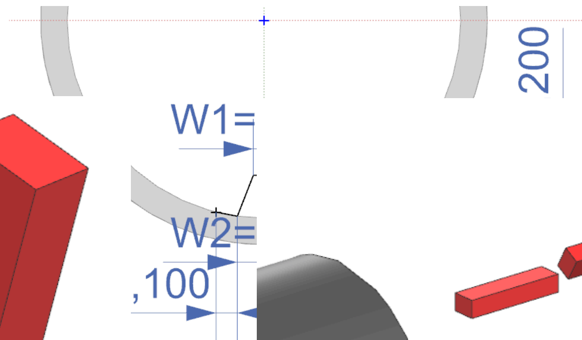


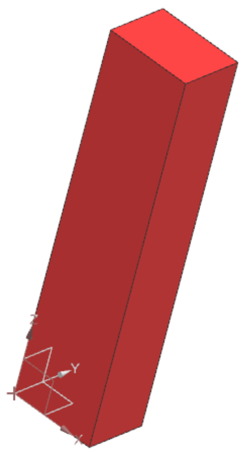
Fig 17. Front view of the stiffener design - 02

Stiffener dimensions

The key dimensions taken from the sketch are:

- **Crown width (W_1):** 0.1 inch
- **Base width (W_2):** 0.25 inch
- **Stiffener height (h):** 0.2 inch
- **Thickness (t):** 0.06 inch





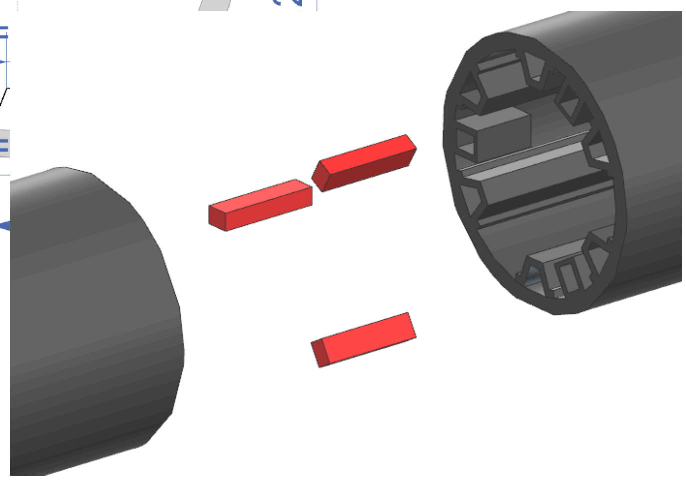


Fig 18. Stiffener dimensions

Fig 19. Assembly pin

Fig 20. Fuselage assembly with pins (red)

Mesh details

A 3D mesh was generated for the full assembly in NX Nastran. Each fuselage section was meshed individually, and mesh mating conditions were applied at the interfaces to ensure that the sections behaved as a single continuous body under loading.

Key mesh properties:

- **Element type:** 3D tetrahedral elements
- **Mesh density:** 0.256 inches element size
- **Mesh connections:** Tied between one-way and two-way sections of each fuselage contact face

- This meshing approach allowed the analysis to capture local effects around stiffeners as well as global deformation over the entire 34-inch height.

Results (displacement & stress)

The structural integrity of the fuselage cross-section was evaluated using a static Finite Element Analysis (FEA) simulation in Siemens NX. To replicate the specific testing conditions, a total external force of 30 lbf was applied to the assembly. The accompanying figures illustrate the deformation progression: the image on the left depicts the structure in its initial, unloaded state (Animation Frame 1), where the displacement is zero (indicated by the blue contour). The image on the right displays the structure under the full 30 lbf load (Animation Frame 30). The color-coded nodal magnitude plot highlights the deformation distribution, with the red contours representing the areas of peak deflection. The simulation yielded a maximum displacement of 3.472E-03 inches (approximately 0.0035 inches). This minimal deflection value indicates that the fuselage design, reinforced by the internal hat stiffeners, maintains high stiffness and structural stability under the applied load.

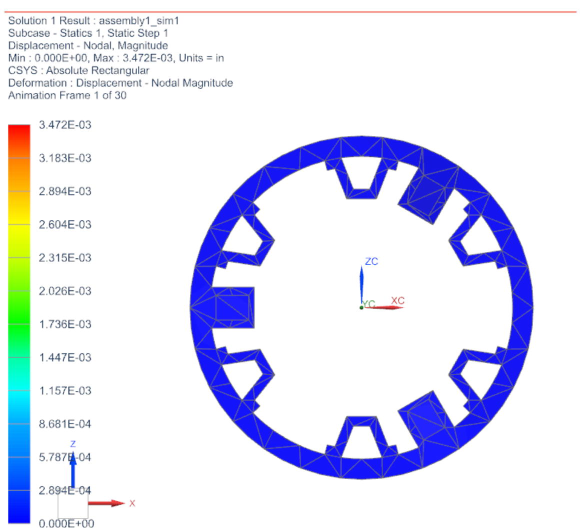


Fig 21. Fuselage under unloaded state

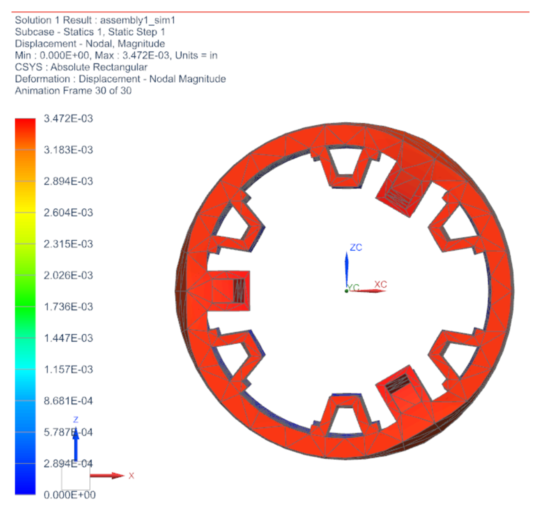
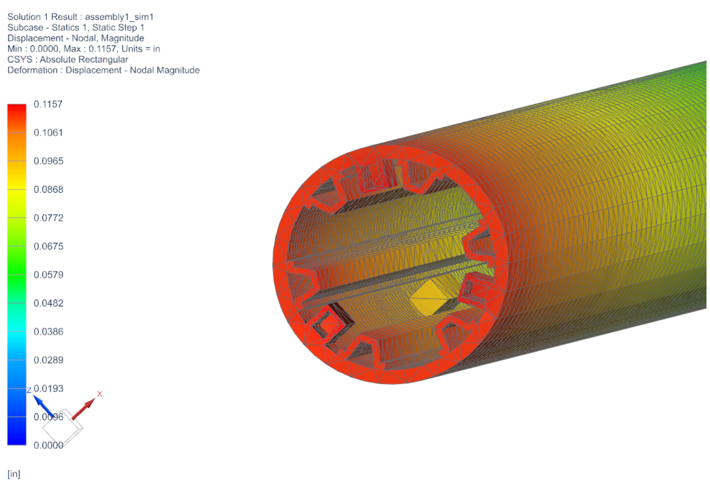


Fig 22. Fuselage under loaded state

To evaluate the structural endurance of the fuselage under extreme operating conditions, a secondary Finite Element Analysis (FEA) was performed with a significantly increased total applied force of 1000 lbf. The results of this high-load simulation are presented in the accompanying figures. The displacement analysis (left image) reveals that the structure experienced a maximum nodal displacement of 0.1157 inches. The color contour plot indicates that the deformation is distributed along the length of the column, with peak deflection occurring at the regions furthest from the constraints. The stress response was evaluated using the Unaveraged Von Mises criterion (right image) to identify potential failure points. Under the 1000 lbf load, the assembly exhibited a maximum stress magnitude of 1949.90 psi. Despite the heavy loading, the stress distribution suggests that the internal hat stiffeners effectively distribute the load, preventing localized stress concentrations that could lead to immediate catastrophic failure.



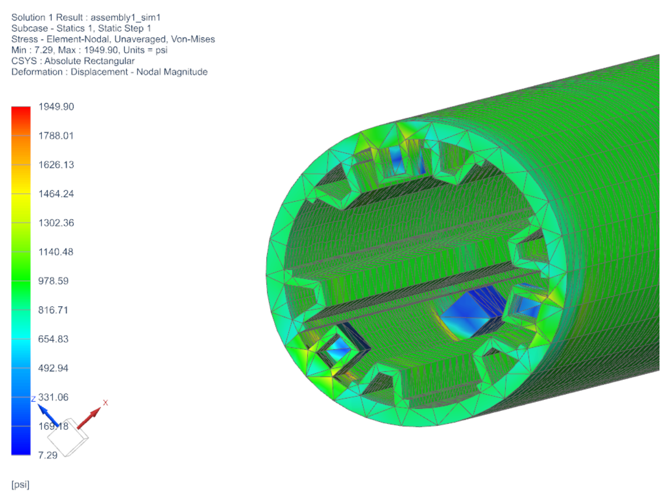


Fig 23. Displacement *Fig 24. Von-Mises Unaveraged*

5.6 Model Variation - 03

The fuselage in Model Variation 03 uses a cylindrical cross-section and is built as a modular assembly consisting of six individual fuselage segments, each 5.7 inches in height, resulting in a total assembled length of approximately 34.2 inches.

To join the segments, a trapezium-shaped connector pin was designed to slide into the internal hat stiffener cavity. The cross-section of this pin was intentionally modeled with a 0.2 mm offset (slightly smaller) to compensate for layer spreading inherent in FDM 3D printing, ensuring a snug and repeatable fit during assembly.

Following experimental compression testing, the resulting failure modes will be analyzed to identify local weaknesses, after which the model will be reinforced and optimized accordingly.

Geometry

The selected fuselage geometry for Model Variation 03 consists of six modular sections designed to assemble into the full length while fitting within a 3D printer build volume of 6 × 6 × 6 inches. Each section uses a cylindrical outer diameter of 2.1 in and a wall thickness of 2 mm to balance structural performance with printability and assembly tolerances.

Stiffener Dimensions

The hat stiffener was designed with a 4 mm crown width, 8 mm base width, and 4 mm height, with a 2 mm wall thickness matching the fuselage shell. No external flange was used because, in FDM printing, the stiffener could be fully integrated into the fuselage inner surface and printed as a single continuous geometry. This eliminated the need for bonded or attached flanges while ensuring smooth load transfer and improved printability.

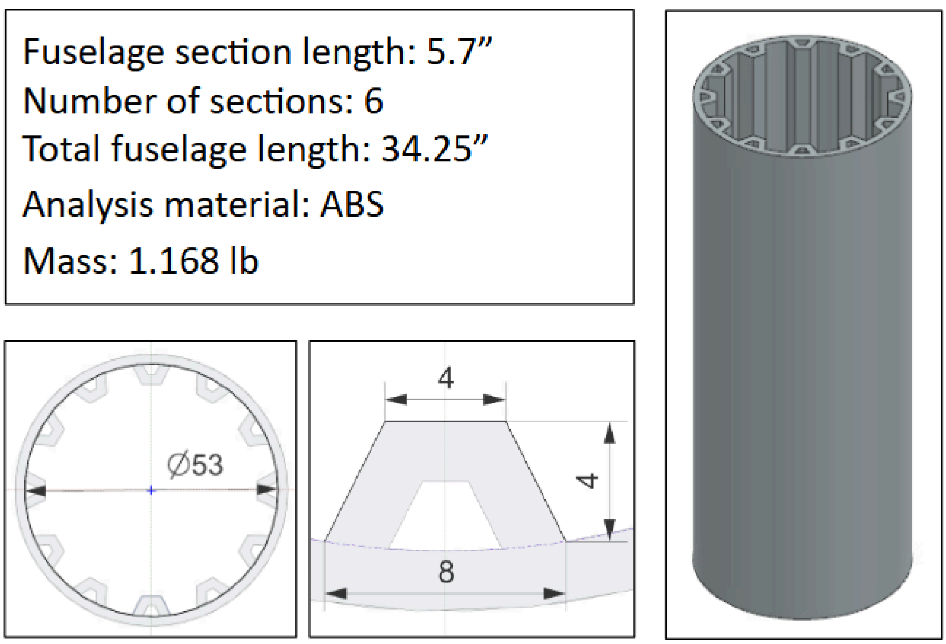


Fig 25. Fuselage and Stiffener Dimensions

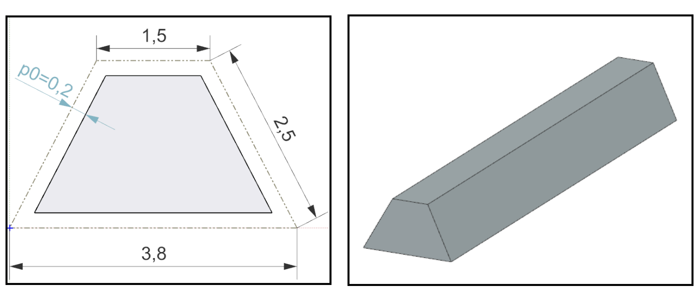


Fig 26. Pin Dimension

Mesh Details

A mesh size of **3 mm** was used for this model, providing sufficient resolution to capture the thin-walled fuselage shell and the 4 mm hat stiffener geometry while keeping computational cost reasonable. A 3D tetrahedral mesh was applied throughout the fuselage sections, with the stiffener skin interface receiving slightly denser refinement due to geometry curvature.

Fig. Meshing

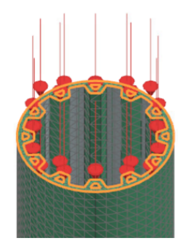
Load Cases

Include the same load cases used elsewhere in the study to maintain consistency: 30 lbf (qualification/crumple zone), 100 lbf (performance metric), and an extreme verification load if needed for sensitivity checks.

Results (Displacement & Stress)

A series of axial compressive loads ranging from **30 lbf to 400 lbf** were applied to evaluate linearity, stiffness, and structural behavior. The corresponding displacement and stress values (force–strain–stress) recorded during the simulation are as follows:

- **30 lbf → 0.1 in displacement → 0.386 MPa**
- **50 lbf → 0.167 in displacement → 0.644 MPa**
- **100 lbf → 0.333 in displacement → 1.288 MPa**
- **200 lbf → 0.666 in displacement → 2.576 MPa**
- **400 lbf → 1.333 in displacement → 5.151 MPa**



These results show a linear increase in strain and stress with applied load, indicating elastic behavior across the full loading range. Peak stress values can be inserted once post-processing is completed.

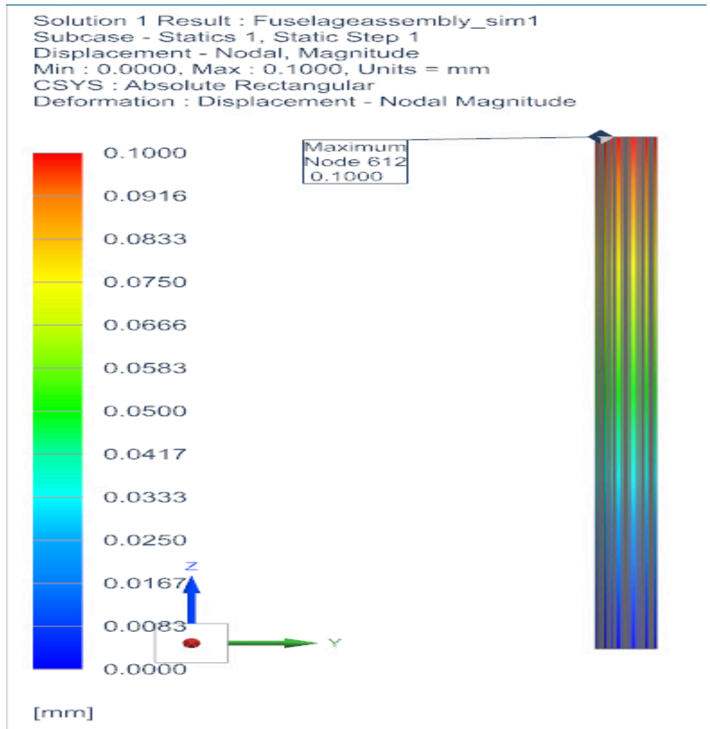


Fig 27. Displacement contour of the fuselage design - 03

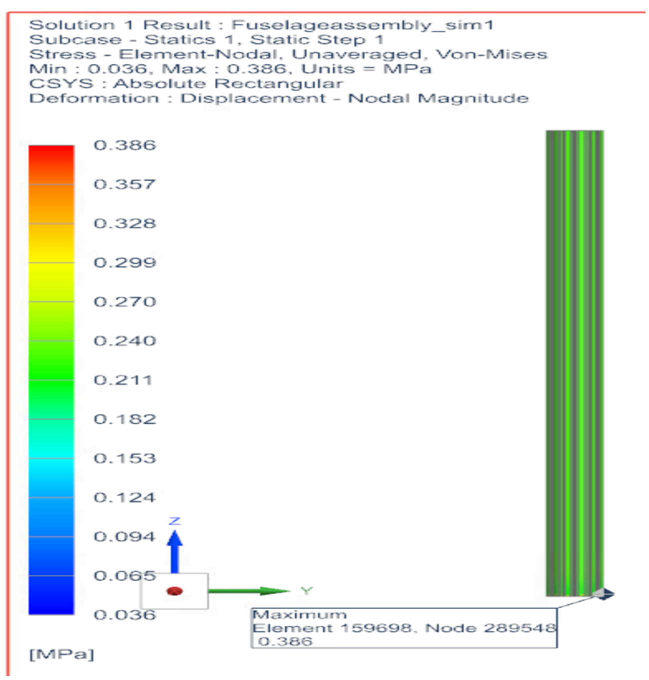


Fig 28. Stress contour of the fuselage design - 03

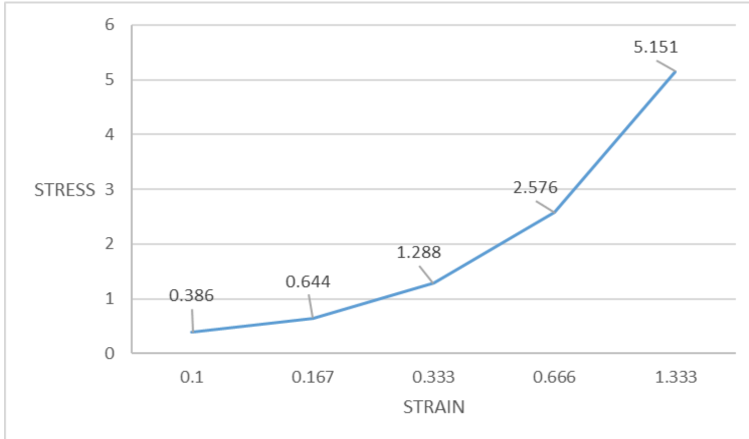


Fig 29. Linear increment in Stress Vs strain curve

5.7 Result Interpretations

5.7.1 Strength Comparison

The strength of each design is evaluated using the maximum von Mises stress under the applied loading. Design 1 shows a maximum stress of 0.657 MPa, which is the highest among the three models. This indicates that Design 1 experiences the greatest internal stresses and is therefore the most likely to reach material failure first under increasing load.

Design 2 has a lower maximum stress of 0.403 MPa, showing a significant reduction in stress compared to Design 1. This suggests that the load is more evenly distributed through the structure.

Design 3 exhibits the lowest maximum stress of 0.386 MPa, indicating the best stress performance of the three designs. From a purely stress-based strength perspective, Design 3 demonstrates the most favorable stress behavior, followed closely by Design 2.

5.7.2 Displacement Comparison

Displacement is used as a measure of overall structural stiffness. Design 1 experiences the smallest maximum displacement at 0.0189 mm, indicating that it is the stiffest of the three designs. This low displacement is expected due to its larger material volume and thicker structural features.

Design 2 shows a higher displacement of 0.0863 mm, which indicates reduced stiffness compared to Design 1 but still within a controlled deformation range.

Design 3 has the largest displacement at 0.100 mm, making it the most flexible of the three designs. While increased displacement is not always undesirable, excessive deformation can lead to instability under compression. Therefore, in terms of stiffness alone, Design 1 performs best, followed by Design 2 and then Design 3.

5.7.3 Weight vs Strength Efficiency

Weight plays a critical role in the efficiency of each design. Design 1 is the heaviest at 4.06 lb, while also exhibiting the highest stress. This indicates poor strength-to-weight efficiency, as it uses significantly more material without achieving superior stress performance.

Design 2 weighs 1.35 lb, representing a large weight reduction compared to Design 1 while also achieving much lower stress. This makes Design 2 substantially more efficient from a structural standpoint.

Design 3 is the lightest at 1.16 lb and also shows the lowest maximum stress value. This means Design 3 provides the best strength-to-weight efficiency of all three designs. Despite having the highest displacement, its low stress and minimal weight make it the most structurally efficient option.

5.7.4 Final Selected Model and Justification

After comparing strength, displacement, stress, and weight efficiency, Design 3 is selected as the final model for fabrication and testing. While Design 1 provides the lowest displacement, it is significantly heavier and experiences the highest stress, making it inefficient for a lightweight compression structure. Design 2 offers a strong balance between weight and mechanical performance, but it is still heavier than Design 3 with slightly higher stress.

Design 3 achieves the lowest stress and lowest weight, which results in the best overall structural efficiency. Although it experiences the highest displacement, the deformation remains within acceptable limits for the intended compression testing. The combination of low stress, minimal material usage, and competitive stiffness makes Design 3 the optimal choice for the final prototype.

6. 3D Printing Methodology

6.1 CAD to STL Conversion

All designs are created in CAD and converted to STL format for additive manufacturing. During export, a high-resolution STL setting is used to accurately capture curved surfaces and fine stiffener features without excessive file size. Proper part orientation is considered to improve printing quality, reduce the need for support material, and align the primary load direction with the strongest print axis when possible. Geometric tolerances are also carefully applied to ensure proper fit between stacked segments and mating features. A small clearance is included at all interfaces to account for printing variability and thermal shrinkage of the material.

6.2 Slicing Parameters

- **Printer:** All components are printed using an FDM-based 3D printer. The printer build envelope constrains each individual segment to fit within a 6 in × 6 in × 6 in volume, which requires the full column to be manufactured as multiple stackable sections.

- **Material:** PLA is selected for all in-house prototype printing due to its strong combination of print reliability, dimensional accuracy, and favorable mechanical stiffness. PLA exhibits a relatively high elastic modulus compared to many other common desktop printing materials, which allows printed parts to resist elastic deformation and maintain their shape under compressive loading. This stiffness makes PLA well suited for evaluating buckling behavior, overall column stability, and geometric load paths during early structural testing. In addition, PLA produces consistent layer bonding and smooth surface finishes, which contributes to more repeatable mechanical behavior between prototypes. These properties make PLA an effective material for both rapid iteration and preliminary structural performance evaluation, not just geometric fit validation. According to the competition requirements, all final official test specimens are printed in ASA by the organizers to ensure consistent standardized testing conditions across all entries.

- **Infill:** A 30 percent sparse double-dense infill pattern is used for all printed components. This locked parameter provides a balance between structural strength and weight while maintaining uniformity across all competing designs.

- **Nozzle size:** A standard nozzle diameter is used to maintain consistent extrusion width and dimensional accuracy. This nozzle size allows for reliable printing of both thin shell regions and internal stiffener features without clogging or under-extrusion.

- **Layer height:** A moderate layer height is selected to balance surface quality and printing time. This setting ensures adequate interlayer bonding while maintaining reasonable build times for each segment.

- **Support strategy:** Support material is used only where required by overhanging geometry. Wherever possible, the design is optimized to minimize or eliminate support structures. Any trapped support material that cannot be removed prior to testing is considered part of the structure and contributes to the total weight.

7. Experimental Testing

7.1 Test Setup

The experimental testing of the compression column was conducted using a standard vertical load frame with two parallel steel platens that apply an axial compressive load to the structure. The column is positioned upright between the platens and is compressed under displacement control until failure.

7.2 Testing Procedure

The test follows a two-stage loading protocol. In the first stage, the fully assembled column is initially set at a height of 34 ± 0.25 inches and must support a minimum load of 30 lbf. While maintaining this minimum load, the column is compressed downward by the top platen through a 6-inch displacement, which defines the required "crumple zone." Throughout this displacement, the column must continuously support at least 30 lbf at all intermediate heights. This first stage functions as a pass–fail requirement. Any column that fails to meet this minimum load at any point during the crumple zone is considered failed and is disqualified regardless of performance in later stages.

Following successful completion of the crumple zone requirement, the column enters the second stage of testing. At a compressed height of 28 ± 0.25 inches, the structure must support a minimum load of 100 lbf. Beyond this minimum threshold, the column is then further compressed, and the maximum load supported at the 28-inch height becomes the primary performance metric used for final scoring. The platen displacement rate is held constant at 7.2 inches per minute to ensure uniform loading conditions for all entries.

7.3 Measurements Collected

7.3.1 Load vs. Displacement

The primary quantitative dataset collected during testing is the applied compressive load as a function of platen displacement. This load–displacement response provides direct insight into the global stiffness of the column, its elastic behavior during the initial loading phase, and the onset of nonlinear deformation as instability develops. The curve is used to identify key performance points including the crumple zone load capacity, stiffness degradation, and peak load at the 28-inch compressed height. These values are later used to calculate the normalized load-to-weight performance metric for competition scoring.

7.3.2 Failure Point

The failure point is defined as the displacement and corresponding load at which the column experiences either a sudden loss of load-carrying capacity, unstable buckling, or catastrophic material fracture. The peak load recorded immediately prior to this load drop is identified as the maximum supported load at the final compressed height. This value serves as the primary experimental validation point for comparison against the finite element analysis predictions.

8. Results

(Will be added after this actual testing is done)

9. Conclusions

(Will be added after this actual testing is done)

11. References

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12. Appendix

A.1 Additional Figures

A.2 Raw FEA Data

A.3 3D Printing Slicer Screenshots

A.4 Test Machine Readings