# Structural Analysis of Satellite Launch Vehicle for Aerospace Applications

A Final Year Project Report

Presented to

**SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING**

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Partial Fulfillment
of the Requirements for the Degree of
Bachelor of Mechanical Engineering

by

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## ABSTRACT

Pakistan does not have its own satellite launch vehicle yet, so we are helping our industry to develop one. Our project "Structural Analysis of Satellite Launch Vehicle for Aerospace Applications" includes the aerodynamic analysis of the exterior of the rocket and the structural analysis of the body to find out that the 3D model of the rocket made holds valid for the applied loads that the rocket will undergo during its flight.

The next step will be the development of the model for tunnel testing and then making an actual rocket but that also includes other systems such as control system, propulsion system which are beyond our scope this project.

## ACKNOWLEDGMENTS

First, we are thankful to Allah Almighty for enabling us to work on this project and write this report and we are also thankful to our advisor Dr Niaz Bahadur Khan and our industrial supervisor Sir Abdul Rafay who helped us a lot in doing research about this project and we learned a lot while working on this project.

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## ABBREVIATIONS

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| FEA | Finite Element Analysis |
| MPa | Mega Pascals |
| Cd | Drag Coefficient |
| Cl | Lift Coefficient |
| max Q | Maximum dynamic pressure |
| FOS | Factor of safety |

## NOMENCLATURE

| | |
|---|---|
| V | Velocity ($\frac{m}{s}$) |
| ρ | Density ($\frac{kg}{m^2}$) |
| $\sigma_Y$ | Yield Strength (MPa) |
| $\sigma_A$ | Maximum Applied stress (MPa) |

# CHAPTER 1: INTRODUCTION

A Satellite launch vehicle is the vehicle that carries the satellite outside the atmosphere of the earth into the orbits and releases them in that orbit. A Satellite launch vehicle carries a large mass of satellite at very high heights. The basic working principle of a launch vehicle is based on Newton's third law of motion which states that "to every action there is an equal and opposite reaction". The combustion of fuel present in the launch vehicle produces gas because of combustion, this gas expels rapidly through nozzles that are located at the rear side of the launch vehicle. The gas does the action or applies force downward and as a reaction the upward force called thrust acts on the vehicle. This thrust drives the vehicle in the upward direction towards the space and thus the action-reaction pair makes launching possible. The structure of the satellite launch vehicle depends on the payload and the height or radius of orbit.

Pakistan has no proper satellite launch vehicle till now. So, our main focus is to make a highly efficient and reliable launch vehicle that fulfills the increasing demands in today's information and technology world. These types of developments will be the backbone of the economy of our country and our goal is to make such types of launch vehicles that can compete with the standards of SpaceX and NASA.

A launch vehicle can have various stages which power it through different parts of the journey until it deploys the satellite into its specified orbit around the earth. These stages have their own separate fuel storages which are utilized orderly. The first stage has large rocket boosters which take it out of the thick atmosphere and then the further stages guide its path to its destination.

The launch vehicle i.e., rocket can be partially or fully reusable. We are developing a fully reusable rocket that can be used to launch satellites by our aerospace industry into orbits repeatedly with less requirement for maintenance and replacement of parts. This will make the whole process of satellite launch more easy, smooth, and cost-efficient.

Our focus in this project is to perform the structural analysis of a Satellite Launch Vehicle. We must prepare a finite element model of the body of a Satellite Launch Vehicle and perform its analysis on ANSYS. The analyses to be performed are

- Finite Element Analysis
- Static Structural Analysis
- Transient Structural Analysis
- Vibrational Analysis (Modal and Harmonic)
- Computational Fluid Dynamics (CFD) Analysis.

The purpose of performing all these analyses is to check for the strength and stability of the Satellite Launch Vehicle. The mesh on the body has to be refined very well in order to achieve accurate results.

The Static Structural Analysis is performed to check that the body can withstand all the loadings which are subjected to it. For instance, the pressurized cabin/ vessels can withstand the pressure of internal fluid (mostly rocket fuel) and all the stresses are within the safe limits.

The Transient Structural Analysis is performed to check that the body can withstand the variable loads which are being applied to the body during its flight.

The Vibrational Analysis (Modal and Harmonic) is performed to determine the natural frequencies of the launch vehicle and its response due to the application of the harmonic force because variable loads are being applied to it which are interpreted as harmonic forces in this analysis. Thus, the stability of the body of the launch vehicle is checked to eradicate any possible failure due to harmful vibrations.

The Computational Fluid Dynamics (CFD) Analysis is performed to simulate the exterior flow of air over the body during its flight. The design parameters are evaluated which are coefficients of lift and drag. The in-flight stability parameters of the body like its pitch, roll, yaw, center of gravity and center of pressure are assessed in this analysis.

After performing all these analyses, the design of the Satellite Launch Vehicle is confirmed for its strength, working and stability.

The practical applications of our project are in the field of aerospace and defense systems of the country. This designed Satellite Launch Vehicle can be used by our aerospace industry for launching satellites into low earth orbit for communication purposes and also for gathering data for defense purposes.

# CHAPTER 2: LITERATURE REVIEW

## The Evolution of Rocket Technology with the passage of time:

Brief history of evolution of rocket science has been discussed in this section and how the propulsion system range and other parameters brought in use for the first rocket. It is explained below:

### Chinese Fire Arrows

First time Chinese apparently used primary form of gunpowder for explosions. The tubes of bamboo and leather with one end closed were used to be filled with gun powder. On igniting the gun powder a series of spark was produced. That was discovery of rocket. In the fight against Mongol invaders these small rockets were bind to arrows in 1232.

## The Birth of Rocket Science:

Later on, in $16^{th}$ century a scientist Galileo said that continuous force is not necessary to keep an object in motion. He said that this happens because of inertia which resist changes in velocity.

After Galileo Sir Isaac Newton packed all rocket science in three laws. Those laws proved to be significant in all modern rocket science.  In “Rocket Principles” chapter focuses on these laws and “Practical Rocketry” chapter states the applications of these laws.

In 18th century Colonel William Congreve became the head of British army rocket companies. Some rockets had the range of about 6 kilo Yards. He manufactured both short and long ranged rockets for his army.

## Modern Rocket Pioneers:

The father of cosmonautics and human spaceflight, Konstantin Tsiolkovsky, recommended liquid propellant rocket engines, orbital space stations, solar energy, and colonization of the solar system. He published “Research into interplanetary space by means of rocket power” in 1903. He used Newton’s second law of motion to derive an equation that relates exhaust velocity and vehicles velocity itself.

## The Space Age Begins:

The space race between US and Soviet Union begins after World War II. First Soviet Union launched **Sputnik I**, with spherical design and four antennas, satellite on October 4, 1957. After two months of first launch, **Sputnik II** set foot in space.

In 1958 US sent **explorer I** into space and discovered Radiation Belts.

America’s **X-15** launched in space in 1959 and 1968 broke many records which includes high speed (7,274 kph or 4,520 mph) and altitude records (108 kilometers or 67 miles). Neil Armstrong was also one of twelve X-15 pilots.

Saturn V, which was 110.6 m or 363 ft high, consist of a capsule with small propulsion unit for return trip and a two-stage lunar lander, was made for a visit to moon on the challenge of President John F. Kennedy in a joint session of Congress.

Using third Saturn V America build **Spacelab**, laboratories, and quarters for three astronauts, in space. Solar panels were used for fulfilling power needs. The last group stayed in space for 84 days.

One of the most flexible of the commercial and military payload launch vehicles is American Delta with many configurations which includes multiple stages and heavy lift strap-on boosters to increase payload capacity to upper orbits. The **Delta family** has done more than 325 launches, with a success rate over 95 percent.

## The Space Launch System and a New Era of Commercial Space Flight:

### NASA's Mighty Saturn V:

The ruling champion of giant rockets is NASA's massive Saturn V, a three-stage booster used to launch American astronauts to the moon in the late 1960s and early 1970s. It was 363 feet (110 meters) high, and the most powerful rocket ever built, even though the last one flew in 1973. Its payload’s launching capacity is up to 45 tons to the moon, or 120 tons into Earth orbit. It weighed 6.5 million pounds (3 million kg) fully fueled at liftoff. That last Saturn V was a modified version that launched NASA's Skylab space station.

### SpaceX Falcon Heavy:

SpaceX's Falcon Heavy rocket is however not the tallest but the most powerful rocket among the group of rockets of 21st century. Using two side boosters based on company's Falcon 9 workhorse and central core, it has the ability to launch 141,000 lbs. Falcon heavy's design is reusable and this is one of the biggest bonuses over other rockets. SpaceX built the first-stage boosters to return to Earth for land or drone ship landings

### NASA's Ares 1 Rocket/Liberty Booster:

NASA launched the tallest rocket of 21st century, Ares 1. It was lunched to validate the design to launch its Orion capsule on moon missions for the now-scrapped Constellation program. The Ares 1 rocket was 327 feet (100 meters) high — 14 stories taller than NASA's space shuttles. But the 2009 flight was the only trip for the Ares 1 design.

### NASA's Space Launch System:

To launch the agency's Orion space capsule, a vehicle originally drawn up as part of NASA's now cancelled Constellation program for deep space exploration, NASA designed its latest giant rocket, Space Launch System (SLS).

According to NASA officials SLS can also launch cargo, equipment, and science experiment s to earth's orbit and beyond. They said that it will be Saturn V-class rocket. The officials also said that it can be used as backup boosters for visits to LEO.

According to NASA, the initial lift capacity of SLS will be 70 metric tons and about 98 meters tall which is little shorter than the Saturn V, but its lift capacity is expandable to 130 metric tons.

## Exterior design of Rockets:

The outer design of satellite launch vehicles is designed in such a way that the drag force is minimum on it. Reduction in the losses, due to drag forces, is made sure in the rocket shape designing. This is achieved by following ways:

- making the body of the rocket narrower
- making the surface profile streamline so that the flow over it is laminar and drag co-efficient is less
- making the surface shining to reduce surface roughness

The main outer design parameters of the rocket design are:

1. Shape of nose cone.
2. Fin shape and number

**Nose cone shape:**

Being the front end of rocket, nose cone meets the air first. It is like the front end of arrow.

And thus, the resistive force of air against the direction of rocket's motion highly depends on design of nose cone and speed of rocket.

Blunt end shapes offer much more resistance and drag. The slightly rounded cone is better than a blunt end.  The pointed cone reduces drag, but it less effective as compared to the slightly rounded shape. Thus, the best, efficient and appreciated design is slightly rounded nose cone that creates the least drag when flying at subsonic speeds i.e., below the speed of sound.

The different nose cone shapes in order of decreasing drag co-efficient are:

**Blunt end > Pointed corner > Ogive > Parabola**

Slightly rounded shape is the shape of parabola. Thus, the most effective shape of nose cone is parabolic. **Falcon 9** has also parabolic nose cone shape, which is used to deploy payloads like satellites into orbit or on ISS

**Fin shape and number:**

The parts attached to the outside of a rocket are fins. These should not have a leading front edge. They are capable to produce drag but they are used to increase rocket stability and control. Which it to keep the rocket flying in air in the upright direction without any wobble and tumble.

It works like the feathers placed at the tail of an arrow. Thus, increasing drag on feathers and keeping the tail at the back. In this way fins provide stability and controls the direction of rocket.

The different configurations of the fins are following:

- Delta
- Clipped delta
- Parallelogram
- Clipped parallelogram
- Rectangle

When the speed of rocket is less than the speed of sound, fins works best when the leading edge is parabolic and trailing edge is sharp. Hence, the **clipped delta** configuration is preferred.

Depending on the design requirement fins can be two, three, four or six in numbers. The fins are equally spaced. Three fins are generally placed in most rocket designs.

Fins are also used to produce lift. This lift stabilizes and controls the flight of rocket.

## Comparison: NASA's Space Shuttle Stack:

As compared to the huge rockets of the history NASA’s spacecraft may seem small. But in the last 30-years it made good measuring stick when it comes to booster matchups depending on how one measures the shuttles.

On the ground, each NASA space shuttle — there are three in museums today: Discovery, Atlantis, and Endeavour — is about 122 feet (37 meters) long from nose to stern and stands 56 feet (17 meters) tall. They have a wingspan of about 78 feet (23 meters).

On the side of 15-story external fuel tank, the space shuttle was perched in the launch position and flanked by two solid rocket boosters. The shuttle was about 56 meters high on the launch pad from the tip of external tank down to the aft skirts of its twin solid rocket boosters.

The payload bey of spacecraft was 18 meters long with the width of 4.5 meters. Spacecraft could haul huge payloads in orbits and makes the shuttle the only spacecraft which can launch large segments of International Space Station.

Since 1981 after the first launch by Columbia in April, NASA launched 135 shuttles in space. They failed twice. Because of explosion due to leakage of O-ring seal in a solid rocket booster, seven astronauts and a shuttle Challenger were lost in January 1986. After each failure the shuttle Columbia broke apart and NASA started working to increase safety of space shuttles.

The following table shows the comparison of different rockets on the basis of height, material, stages, weight, and payload capacity.

| Rocket Name | Company and Country Name | Height | Material Used | Stages | Weight | Payload Capacity |
|---|---|---|---|---|---|---|
| NASA's Mighty Saturn V | NASA, USA | 363 feet (110 meters) | aluminum | three-stage booster | 6.5 million pounds (3 million kg) fully fueled at liftoff | 45 tons to the moon, or 120 tons into Earth orbit |
| Ill-fated N-1 | Soviet Union | 345 feet (104 meters) | - | five distinct stages | 6.1 million pounds (2.7 million kg) | 95 tons |
| SpaceX Falcon Heavy | SpaceX, USA | 230 feet (70 meters) | aluminum-lithium alloy | two side boosters and a central core | 1,420,788 kg (3,125,735 lb) | 141,000 lbs. (64 metric tons) |
| Delta IV Heavy | United Launch Alliance, USA | 235 feet (72 meters) | aluminum trisector | three boosters | 732 tons at liftoff | 24 tons to low-Earth orbit and 11 tons toward the geosynchronous orbits |
| NASA's Space Shuttle | NASA, USA | 184 feet (56 meters) wingspan of about 78 feet (23 meters) | aluminum | three main engines and two solid rocket motors | 2,000,000 kg (4,500,000 pounds) | Maximum 28,803 kg (63,367 pounds) |
| Electron | Rocket Lab, USA | 18m with diameter 1.2m | lightweight carbon composite material | 2 stages | 12.55 tons at liftoff | 150 kg |
| Chang Zheng | CNSA, China | 56.97 m | - | Core + 4 strap-ons | 870 tons | 25 tons |
| Soyuz | Soviet Union | 42.5 m | - | 3 stages | 310 tons | 7 tons |

Figure 1: Comparison of Different Launch Vehicles

## Finite Element Analysis:

At Boeing, M.J. Turner developed the finite element method that is used every day during the time of 1950 to 1962. M.J. Turner worked on the direct stiffness method and generalized it and made it better. Boeing provided the resources for it. At that time other aerospace companies but using the force method. In 1952 and 1953 Turner overlooked the development of finite elements based on first continuum. Some other contributors to this are B. M. Irons, R. J. Melosh and E. L. Wilson. Irons invented shape functions, the patch test iso-parametric models and frontal solvers. R. J. Melosh systematized stiffness elements variational derivation and also worked on Rayleigh-Ritz link. The first finite element method software was also developed by E. L. Wilson. At some part of their careers all of these people were in aerospace industry. Current finite element method origin starts with a paper that was composed in 1956 by Topp, Clough, Martin and Turner which is now being used in many commercial codes. One ingredient of finite element method is digital computation and in the 1950s only large companies had the computational power for finite element method. These amazing scientists for all engineers in the major of structural and they have studied classical mechanics, so their general approach was considering structural elements in the form of force transmitters as it was the standard view at that time.

The next period for finite element method was from 1962 to the year 1972. Melosh was a scientist who presented displacement models Rayleigh-Ritz using minimum P.E principle.

After 1972 it was the time for consolidation. there was a steady progress in hybrid and mixed formulations. There were developments in the formulations for assumed strain. Mesh adaptivity and error estimation techniques were developed because of the mathematical foundations understanding. Finite element method commercial codes gain significance. They provided a good view about how things work in a real world and what does not work in the real world.

The three ingredients that finite element method is made up of today are:

- Matrix Structural Analysis
- Variational Approximation Theory
- Digital Computer

Variational approximation schemes world developed before the development of digital computers. Matrix structural analysis was developed during the 1930s. These ingredients were put together in the 1950s.

## Finite Element Method (FEM) Benefits:

In the product design and development process in specializations under discipline of mechanical engineering like biomedical, aeronautical, or automotive industries, we use integrated finite element method. According to different requirements like thermal structural fluid or electromagnetic, modern FEM packages have specific components. Let's take an example for a simulation of structural purposes, FEM can help in optimizing the design and minimizing the cost materials etc. and it can also provide visualizations for strength and stiffness etc.

Some of the specific capabilities of finite element method are its stress indication, displacement distribution and its detailed visualization of twisting and bending places. Nowadays the software used for finite element method have a ton of options of simulation for modeling and analysis. Finite element method provides us many benefits which include better design, better accuracy, and increased insight into the parameters of critical design, virtual prototyping which results in making less hardware prototype thus saving cost, increased productivity and revenue and a robust and cost-effective design cycle.

Finite element method algorithms are integrated in the modern-day design tools that helps in raising the engineering standards and improving the design process. Any engineering design can be made, tested, and modified according to requirement before making actual hardware prototypes using modern day FEA applications.

**Aerospace Industry:**

In the aerospace industry, FEA has many applications. Rocket structures are made and tested using FEA analysis during its design and development. First the model is developed in design software like SOLIDWORKS or ANSYS. Then mesh is generated the way it is required for solving the structure. The mesh elements vary according to the type of model or geometries as some mesh are suitable for some type of geometries while they may not be suitable for other type of geometries. Different types of mesh elements are developed during the development of finite element analysis. They differ based on two-dimensional or three-dimensional meshing. Different types of elements are:

- Primitive Structural Elements
- Special Elements
- Macro Elements
- Continuum Elements
- Substructures

Substructures can cater complex or big geometries as they are adaptive. Two dimensional elements are triangular and quadrilateral while for 3D, we have trigonal, tetrahedral and 3D quadrilateral elements. For better meshing, the aspect ratio is also important which is the ratio between side lengths of the element of mesh. Transition mesh is also used at interfaces for better meshing as it allows to cater for stress concentrations and achieve better results.

Different mesh elements are shown below:

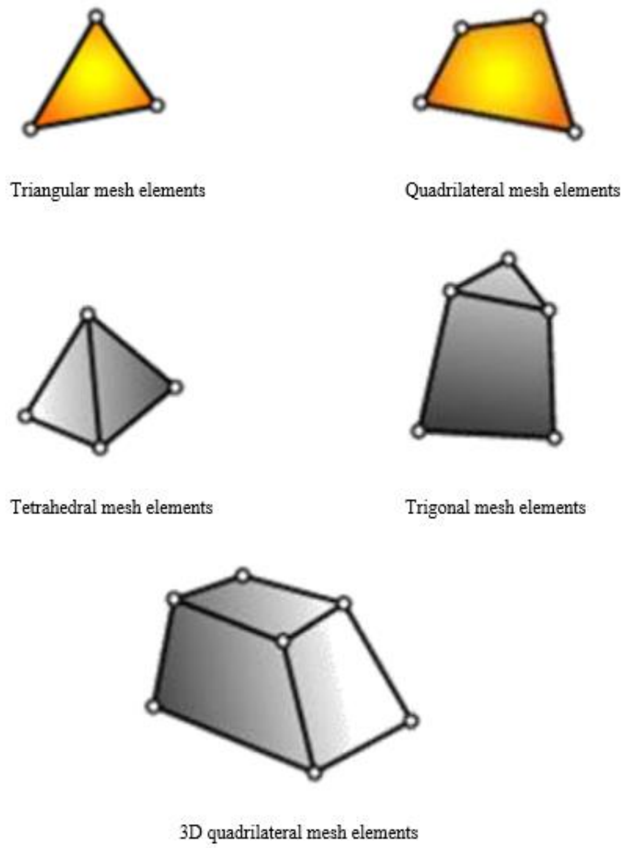


Figure 2: Different mesh Elements

The next step after meshing is to work out the working conditions that the launch vehicles have to experience during the flight. The working conditions include static pressure in fuel tanks or external dynamic pressure and internal loadings. These are applied to the launch vehicle geometry in the software to analyze the effect they will cause on the body, and it is tried to make the simulation as close to real-life conditions as possible. Analyzing the structure in such a way gives us insight into the stress-concentrated regions and whether the structure that we have made is valid for the given working condition or not. The graphs we get give us a glimpse of the real-life conditions and these results then help in developing the actual hardware prototype of the model and then testing it. The actual model is then less likely to fail if the design is optimized and tested first using FEA techniques.

The values of stress of any other parameter like displacement or strain is shown by using a color legend that shows a specific value for specific color. Red is mostly used for the most extreme value of the parameter. Some stress plots of some objects are shown below.

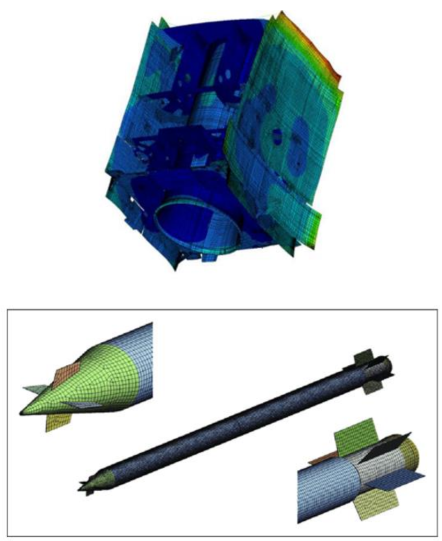

Figure 3: Example Stress Plots

## Computational Fluid Dynamics (CFD):

Using the difficult way of trial and error, refinement and different assessment and validation procedures, the developments of techniques for computational fluid dynamics happened. At imperial college in the early 1973, the cfd group there started on the program for predicting simple shear flows and also jet flows (free and confined). It was a very ambitious program that attempts on predicting flow pattern with flow configurations for both 2d and 3d. Mainly it involved simple parabolic flow without recirculation and using stream function–vorticity solution algorithm, and so it provided non-measurable flow characteristics, so it wasn't exactly able to compare to real life problems.

In late 1973, however, there was a new solution proposed that helped in finding the way using velocity and pressure variables as main parameters. That solution was semi-implicit solution algorithm. It made the momentum equations (navier stokes) solutions easier and straightforward. Up to ten thousand nodes (orthogonal) and grid size that started at 20 by 20 was used in 1000 iterations for symmetrical pipe flow for simplify confined type. In 1974, launder and Spalding developed a model for the representation of flow turbulent characteristics for big Reynolds numbers. Standard k-ε turbulence model was developed because of this which is also called as two equation turbulence model. In 1977, Whitelaw, Khalil and Gosman came up with an article with systematic validation for k-ε model in different applications with swirl and without it. In 1975, Whitelaw, Khalil and Spalding gave the turbulence mode validation for turbulent reacting furnace configuration with swirl and without it. Professor d.b. Spalding in early 1986, delivered a presentation on cfd in education and engineering at Rensselaer polytechnic institute Sadowsky series in New York, USA. In the first development stage resulted in incredible results and the confidence of researchers was improved in using the techniques for applications like in industry or power plants. Using the basic concept developed, several successful implementations were made that were very encouraging.

Mainframe computational limitations were the main thing limiting the progress of computational fluid dynamics at that time. Handling irregular boundaries and wall conditions were difficult with simple orthogonal grid, the convergence was slow and there was numerical diffusion. 3d geometries and calculations that were dependent on time were also very difficult. The developments that happened recently in these past two decades had many applications that also involve aerospace applications like simulations of flights of rockets. Different software is developed and used by experts like design builder, energy plus and Ansys.

In past decades, computational fluid dynamics has been used and studied as a tool intensively for flow simulation over bodies like rockets and planes. Some other techniques like laser-induced fluorescence and particle image velocimetry are also used which allow to obtain both planar and three-dimensional data but they are very costly.

One alternative is numerical modelling because some limitations can be worked around with that. Detailed information can be obtained with it on flow variables for whole flow field data in controlled conditions and without similarity constraints that can occur in other techniques. But there is another matter that need to be account for and that is the how accurate cfd is. In the geometrical implementation of the model, selecting proper strategies for solution and generation of grid, intensive care is required. Moreover, the errors in numerical and physical modelling should be assessed by using validation and verification studies in detail.

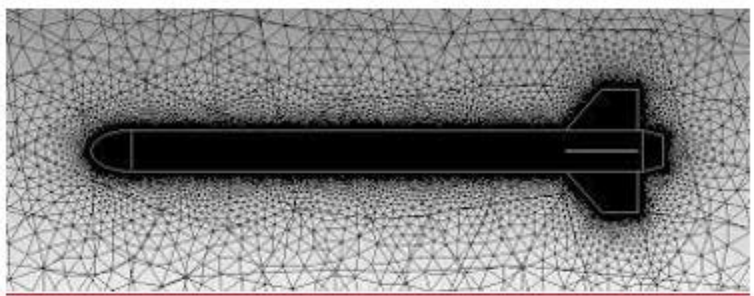

Figure 4: Meshing of a sample Rocket

## NASA Saturn V Rocket (CFD Simulation):

The rocket's flow domain meshing has been done using mesh transition and using finer mesh near the body surface. It is shown below:

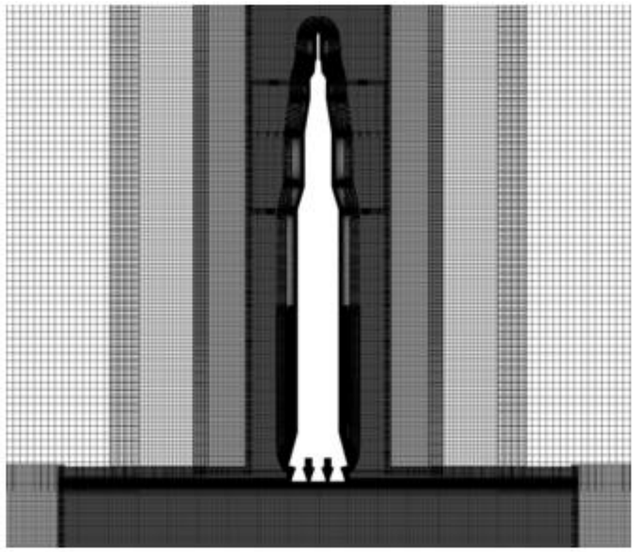

Figure 5: CFD simulation of NASA Saturn V

Below are the results of flow simulations at different Mach numbers:

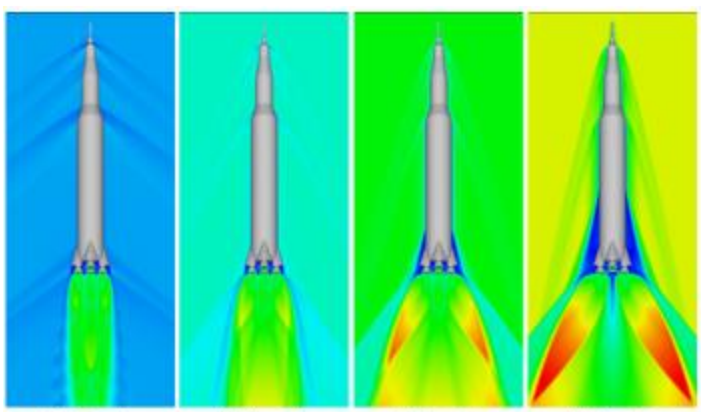


Figure 6: CFD Results at different Mach Numbers

## Vibrational Analysis of Rockets:

In the first stage booster, the thrilling and vibration produced by rocket fuel burning is known as thrust oscillation. These oscillations are in the waves, that propagate over the rocket's length up and down. For rocket design, one big challenge is to develop aviation electronics that can work in such an oscillating environment.

All electronic hardware is tested to withstand such vibration and shock because they can receive such oscillations if they fall or are shaken hard. However, for rockets such vibrations are way harsh and so they need better testing and better equipment and data to develop the best possible equipment which also include the structure of rockets. Vibrations are dangerous and there are cases when such vibrations caused the engine to shut down.

## Modal Analysis of Rockets:

As the vibration analysis is very important in the designing of rockets so modal and harmonic analysis are also performed to find the natural frequency of the rocket structure to make sure that resonance is avoided, and stability of the rocket is ensured. All harmful vibrations should be taken care of, and such analysis should not be neglected so that the rocket can go into space without problems.

Such analysis is particularly important because in many cases, the static structural studies shows that the model is good to go but resonance happens at any part of it that can result in the failure of the model.

# CHAPTER 3: METHODOLOGY

## Different Rocket Systems:

When in flight, there are a lot of force that act on the rocket, those forces are:

- Aerodynamics
- Thrust
- Weight

A rocket has many parts which can be grouped into different systems according to their functions. Mostly, the rocket can be divided into four systems:

- Structural System
- Payload System
- Guidance System
- Propulsion System

The diagram showing all these parts is shown below:

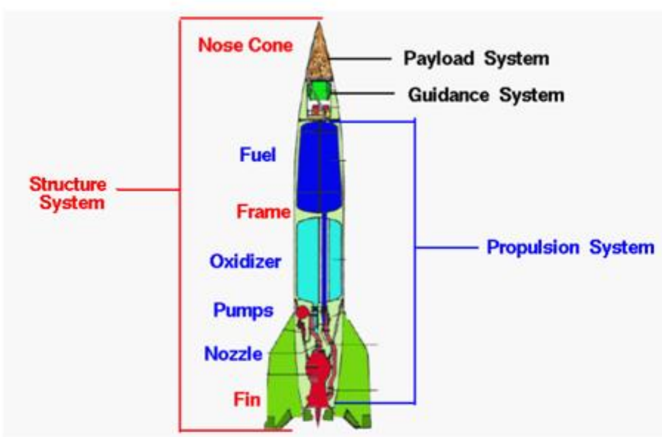


Figure 7: Different System in Rocket

**Structural System:**

Just like an airplane fuselage, the structural system of the rocket is its main frame or body. It is made up of materials like aluminium or titanium which are very lightweight and have long stringers which are along the length of the rocket and they are joined to the hoops that revolves around the rocket's circumference. Then on top of hoops and stringers is the skin of the rocket that makes the rocket's basic shape. The skin is also given a coating of heat shield for keeping the rocket cool during flight. It also maintains the temperatures cool enough for oxidizers and fuels. Some rockets also have some fins for the purpose of stability in flight.

**Guidance System:**

The communication equipment, radars, sensors and on board computers make up the guidance system of a launch vehicle. The guidance system controls the rocket in flight. The guidance system also provides some stability to the rocket so that the rocket does not go out of control during flight. Nowadays the nozzle is controlled and rotated for maneuvering of the rocket.

**Payload System:**

A rocket's payload system is dependent on the mission of the rocket. In early days of rocket development they were mainly used for fireworks, so fireworks were their payloads. During the evolution of rockets, they have been used as weapons with nuclear warheads and now those same rockets are modified and they carry out space missions like weather monitoring, communications, planetary exploration, spying etc so there payloads are mostly satellites and its parts etc. Some rockets are also developed that launch people into orbits and on the moon.

**Propulsion System:**

The major part of a rocket is its propulsion system. Some propulsion systems are solid and some are liquid. This is based on fuel used. Some rockets using solid propulsion system are Titan III, Space Shuttle, Delta II while V2 used a liquid propulsion system.

Apart from the above classification, there are also other ways to classify a rocket's parts. For example for determination of weight and flight performance, structure, payload, guidance and propulsion structure as one weight parameter and the weight of propellant then acts as other factor that changes with time as the fuel burns.

## Project scope:

Our project will cover the structure of the rocket, the propulsion fuel tank and the aerodynamic forces acting on the rocket.

The main objectives of the project are:

- Design a geometry for the the rocket outer structure along with the fuel tanks.
- Refining the rocket geometry to resolve meshing errors
- Meshing the Rocket geometry.
- Structural Analysis of the rocket and the fuel tanks.
- Aerodynamics analysis of the launch vehicle's exterior.

We will not be covering the control and guidance systems of the rocket and also the engine of the rocket.

## Geometry of the satellite launch vehicle:

The rendered image of the geomtery that was finalized for the rocket structure is shown. The geometry is designed on Solidworks. The internal tanks are also shown without the exterior heat shield and the structure.

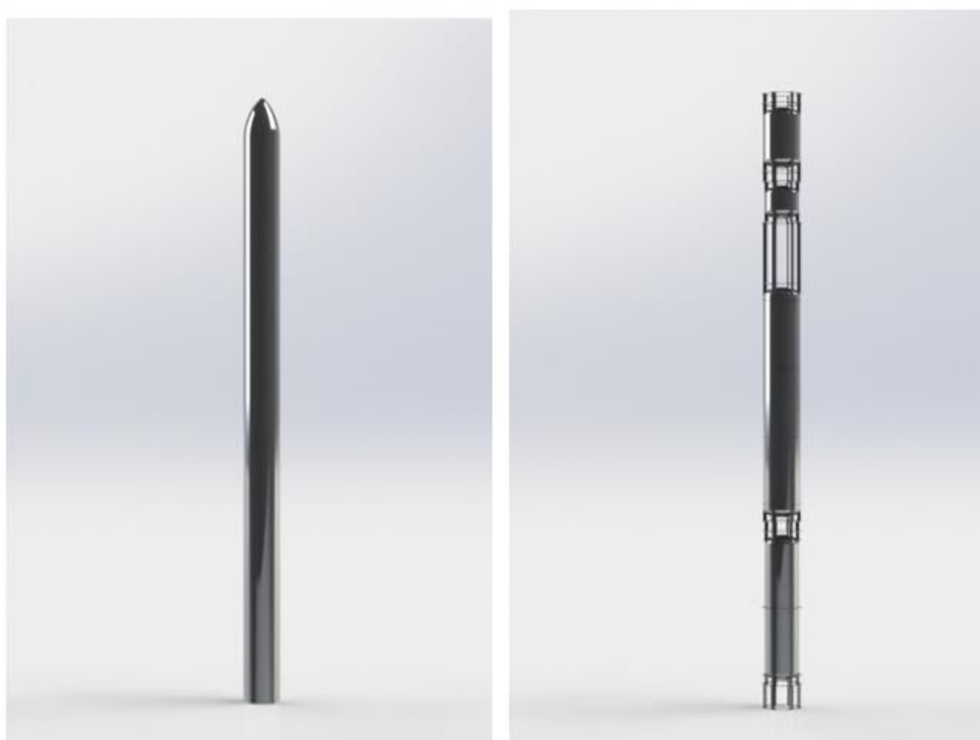

Figure 8: Rocket Rendered View

The drawings of the parts of the model are shown in appendix 1.

The rocket parameters are shown below:

Table 1: Rocket Dimensions

| **Sr #** | **Rocket Parameter** | **Value (mm)** |
|---|---|---|
| **1** | Length | 20,000 |
| **2** | Outer Diameter | 1200 |
| **3** | Inner Diameter | 1196 |
| **4** | Thickness | 2 |

The fuel tanks structure and rendered image are also shown below:

Figure 9: Rocket Tank

The tank parameters are shown below:

Table 2: Tank Dimensions

| Sr # | Fuel Tank Parameter | Value (mm) |
|---|---|---|
| **1** | Length | 4,500 |
| **2** | Outer Diameter | 1020 |
| **3** | Inner Diameter | 1018 |
| **4** | Thickness | 1 |

## Refining the geomtery for the meshing errors:

When the geometry was meshed, there were a lot of errors of the interference.

Those errors were cleared in SpaceClaim before meshing the design.

## Material Selection and Properties:

The most common material now a days using for rockets are carbon fiber and aluminum alloys. We are using Aluminum alloy T6-6061 for our analysis which have following properties:

Table 3: Aluminum T6 6061 contents

| Element | Content (%) (%) |
|---|---|
| **Aluminium / Aluminium, Al** | 97.9 |
| **Magnesium, Mg** | 1 |
| **Silicon, Si** | 0.60 |
| **Copper, Cu** | 0.28 |
| **Chromium, Cr** | 0.20 |

Table 4: Properties of Aluminum T6 6061

| **Properties** | **Metric** | **Imperial** |
|---|---|---|
| **Tensile strength** | 310 MPa | 45000 psi |
| **Yield strength** | 276 MPa | 40000 psi |
| **Shear strength** | 207 MPa | 30000 psi |
| **Fatigue strength** | 96.5 MPa | 14000 psi |
| **Elastic modulus** | 68.9 GPa | 10000 ksi |
| **Poisson's ratio** | 0.33 | 0.33 |

## Computational Fluid Dynamics of the Rocket:

The objective of our project was to perform the complete structural analysis of a satellite launch vehicle to check its strength and in-flight stability. For this purpose, the foremost step was to perform the external CFD (Computational Fluid Dynamics) analysis of the rocket body to determine the response of the body upon the externally applied parameters. They parameters are the conditions that are experienced by the rocket while moving through the Earth's atmosphere.

The software used to perform this **CFD analysis** was **ANSYS Fluent**. The given conditions were applied, and a simulation was performed on the rocket to obtain the flow results. After the CFD analysis, the results were collected and used in other analyses like FEA which were performed on the satellite launch vehicle.

**Geometry:**

Firstly, the geometry of the satellite launch vehicle was imported in the form of a STEP file. The length of the rocket was **20 meters**. The diameter of the rocket was **1.2 meters**. The shape of the nose cone of the rocket was parabolic.

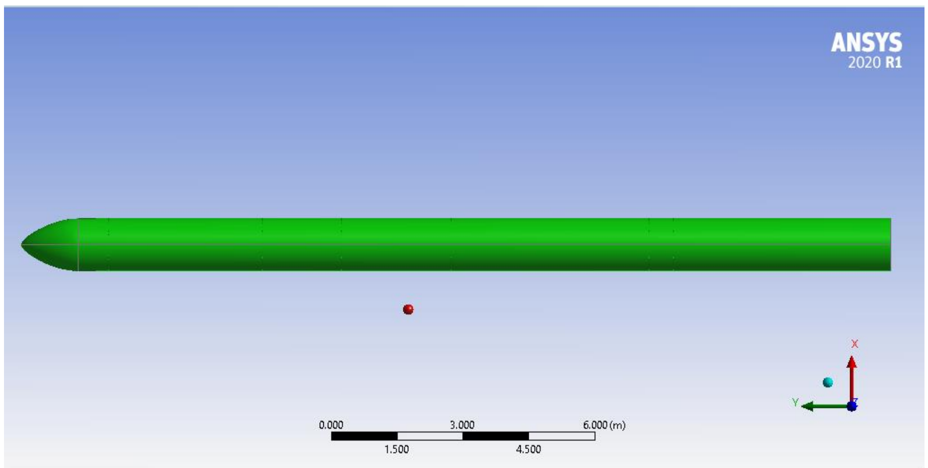


Figure 10: Length of rocket

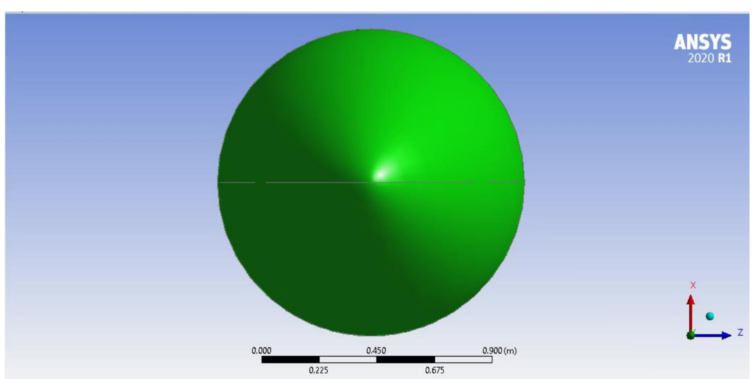


Figure 11: Cross-section of rocket

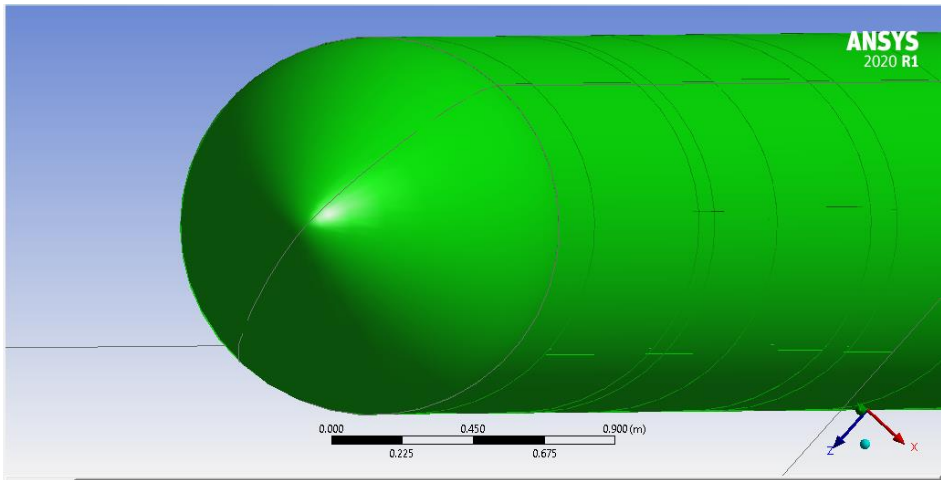


Figure 12: Nose cone of rocket

For performing the CFD analysis, a flow domain was to be created first around the rocket body for making a region through which the air can be simulated to be flowing over it.

An enclosure was created around it with dimensions extending about 4 to 5 times the dimensions of the rocket in the corresponding axes.

The dimensions of the enclosure were **140 m × 13.2 m × 13.2 m**.

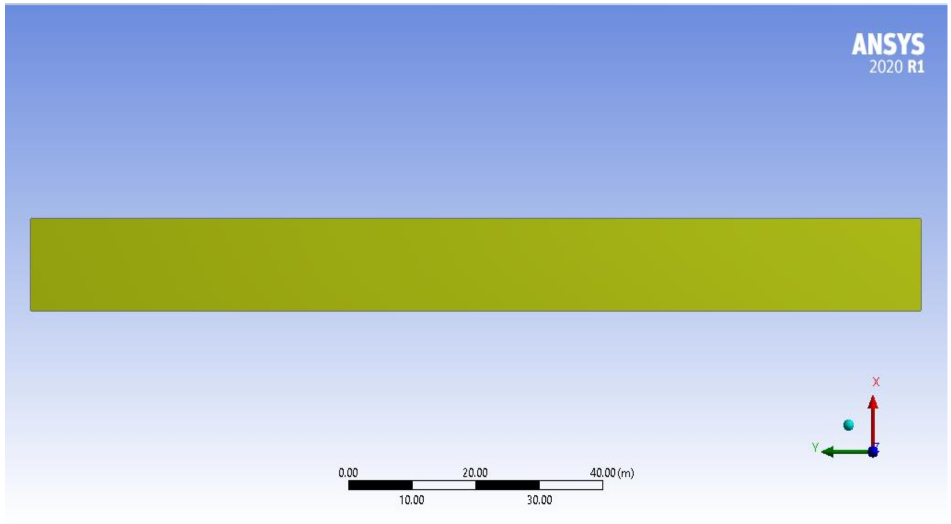


Figure 13: Enclosure for CFD

The rocket body was then subtracted from the outer box using the Boolean command in ANSYS to create the required **flow domain** for the simulation in our CFD analysis. In this way, the geometry was prepared for further steps of the analysis.

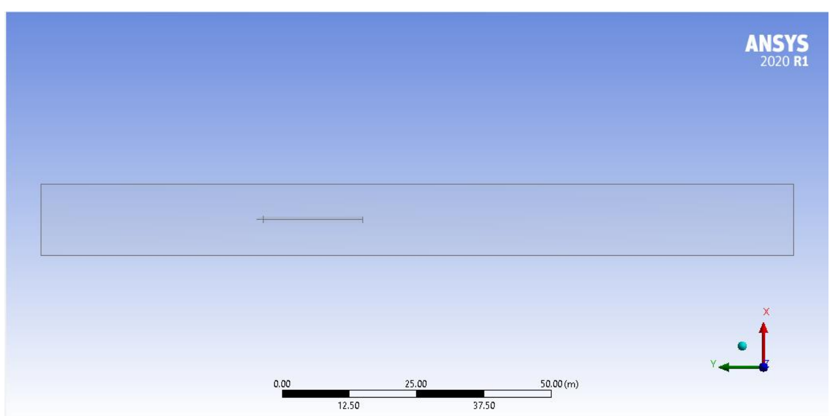


Figure 14: Subtracted Geometry

**Meshing:**

After preparing the desired geometry of the flow domain, the next step was to generate mesh of this whole region to have some data points where the values of different parameters like pressure etc. can be evaluated.

A mesh was created using body sizing with an element size of **0.4 meters** and a mesh growth rate of **1.2**. The unstructured type of mesh was used, and the shape of mesh elements was triangular. The mesh was very fine near the body of the rocket where there is high pressure gradient which need to be captured in order to achieve more accurate results. While a coarser mesh was used far from the body where there are not many fluctuations in the values of parameters.

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | 1 Body |
| **Definition** | |
| Suppressed | No |
| Type | Element Size |
| Element Size | 0.4 m |
| **Advanced** | |
| Defeature Size | Default (2.e-003 m) |
| Growth Rate | Default (1.2) |
| Capture Curvature | Yes |
| Curvature Normal Angle | Default (18.0°) |
| Local Min Size | Default (4.e-003 m) |
| Capture Proximity | Yes |
| Proximity Min Size | Default (4.e-003 m) |
| Num Cells Across Gap | Default (3) |
| Proximity Size Function Sources | Faces and Edges |

Figure 15: Parameters of CFD

The number of mesh elements generated was **above 3 million (3,480,300 mesh elements).**

| | |
|---|---|
| Nodes | 675140 |
| Elements | 3480300 |

Figure 16: Nodes and Elements

Linear element order was used for the mesh elements.

Details of "Mesh"

| | |
|---|---|
| **Display** | |
| Display Style | Use Geometry Setting |
| **Defaults** | |
| Physics Preference | CFD |
| Solver Preference | Fluent |
| Element Order | Linear |
| Element Size | 0.4 m |
| Export Format | Standard |
| Export Preview Surface Mesh | No |

Figure 17: Mesh Details

The **mesh generated** is shown as follows:

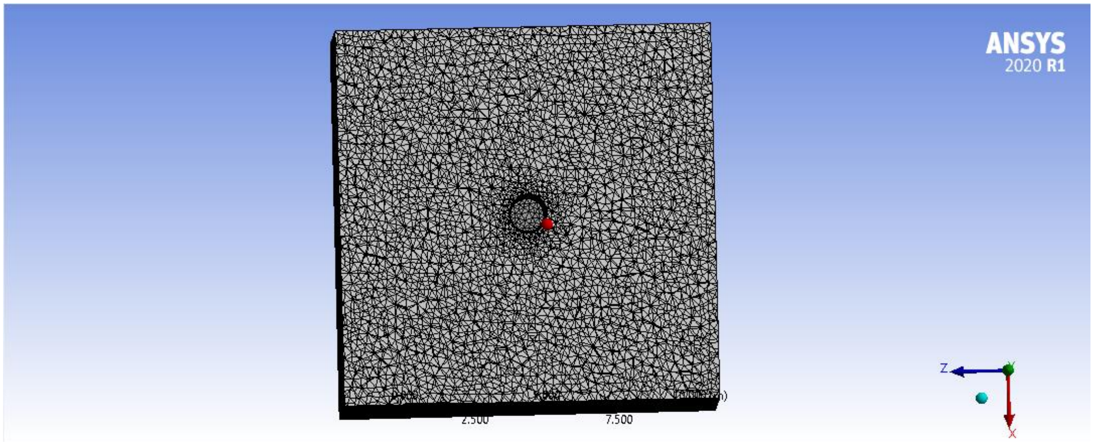


Figure 18: Mesh for CFD

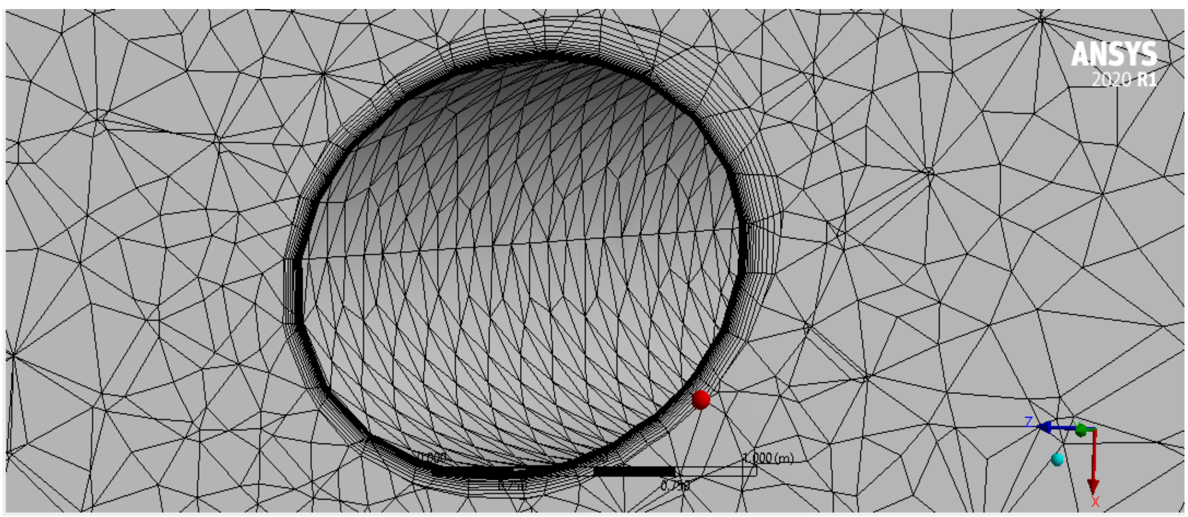


Figure 19: Close up Mesh view

The total **number of inflation layers** included was **60**.

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | 1 Body |
| **Definition** | |
| Suppressed | No |
| Boundary Scoping Method | Geometry Selection |
| Boundary | 3 Faces |
| Inflation Option | First Layer Thickness |
| First Layer Height | 3.9e-006 m |
| Maximum Layers | 60 |
| Growth Rate | 1.2 |
| Inflation Algorithm | Pre |

Figure 20: Inflation Layer Details

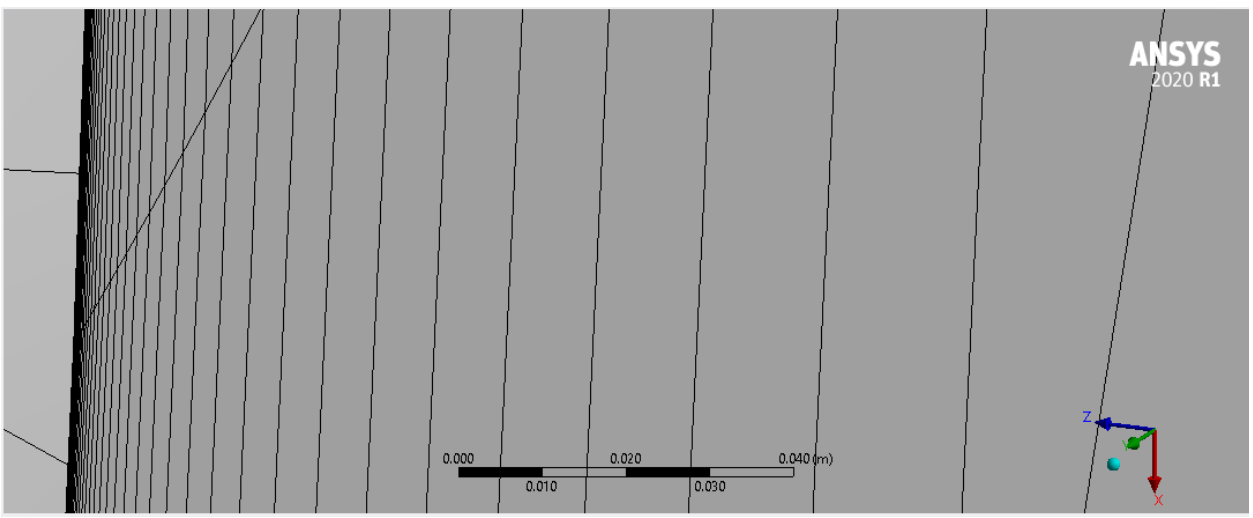


Figure 21: Inflation layers

The **first layer thickness** was used with a thickness of **3.9 × 10$^{-6}$ meters**.

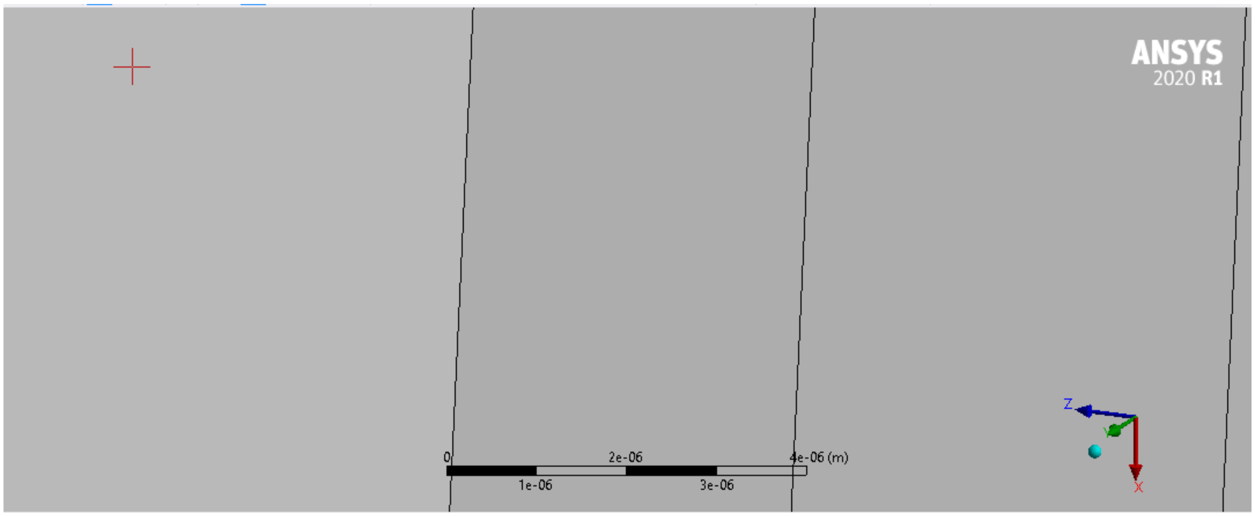


Figure 22: First layer thickness

The inlet of air flow is specified.

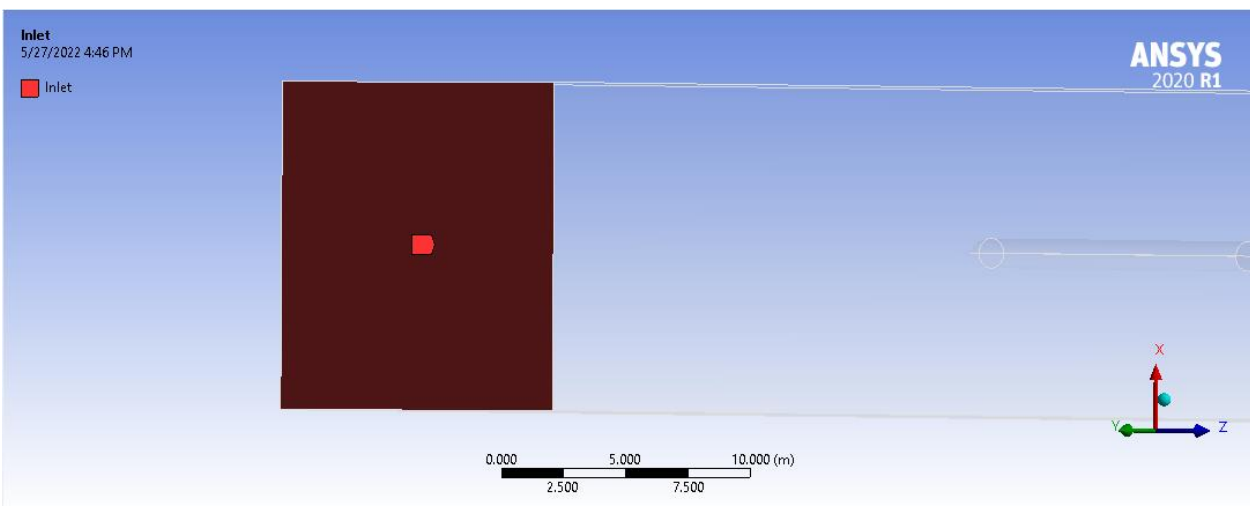


Figure 23: Inlet

The outlet of air flow is specified.

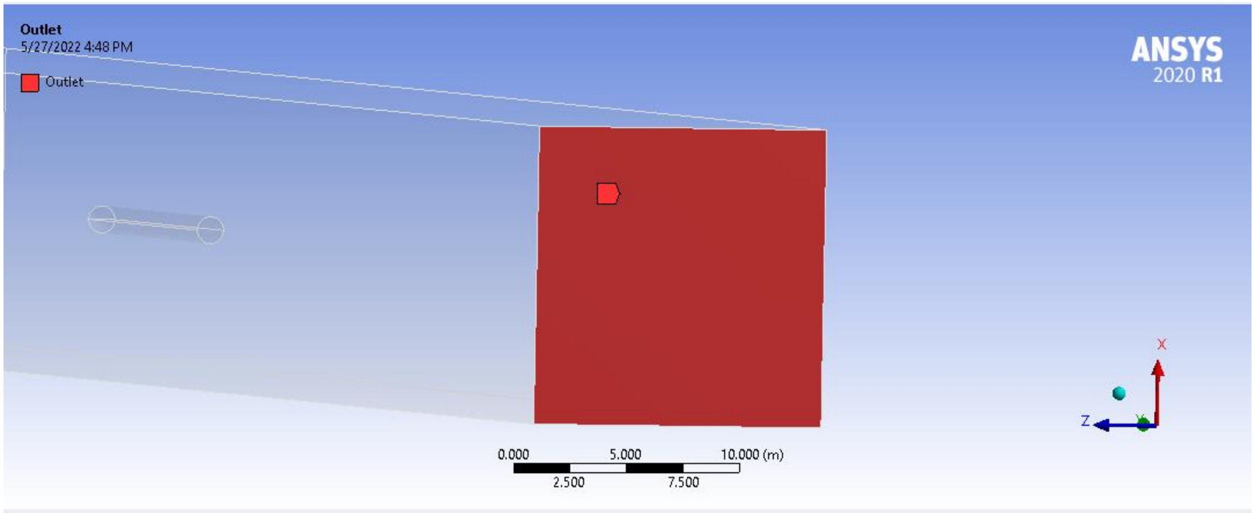


Figure 24: Outlet

**Setup:**

The satellite launch vehicle was being analyzed for its whole journey from the surface of the Earth to into the Lower Earth Orbit (LEO). The most adverse conditions that the rocket was experiencing throughout its journey were the **maximum dynamic pressure or max Q** conditions.

**Dynamic Pressure:**

The formula for the dynamic pressure is:

$$\boldsymbol{Dynamic\ Pressure\ (Q) = \frac{1}{2}\rho v^2}$$

The rocket undergoes the maximum stress conditions when the value of this expression of dynamic pressure is at its maximum. This maximum dynamic pressure occurs at an **altitude** of about **11 km** from the sea level.

The applied conditions on the satellite launch vehicle are:

Table 5: Applied Dynamic Pressure Conditions

| **Parameter** | **Value** |
|---|---|
| *Atmospheric density* | 0.3245 $kg/m^3$ |
| *Static air temperature* | 211.2 K |
| *Total air temperature* | 311.5 K |
| *Mach number* | 1.402 |
| *Dynamic pressure* | 29.41 kPa |
| *Static pressure* | 19.68 kPa |

- **Double precision parallel** type solver was setup for the simulation.
- Since the density of the air varies with altitude, the density of the air is taken from the given conditions to be **0.3245**.

- Since the Mach number was **1.402** which is greater than Mach 1 so the flow of air over it was supersonic. Due to this reason the flow was treated as compressible flow and the **density based** solving method was used.
- The magnitude of **inlet velocity** is **480 m/s** with direction normal to the boundary.

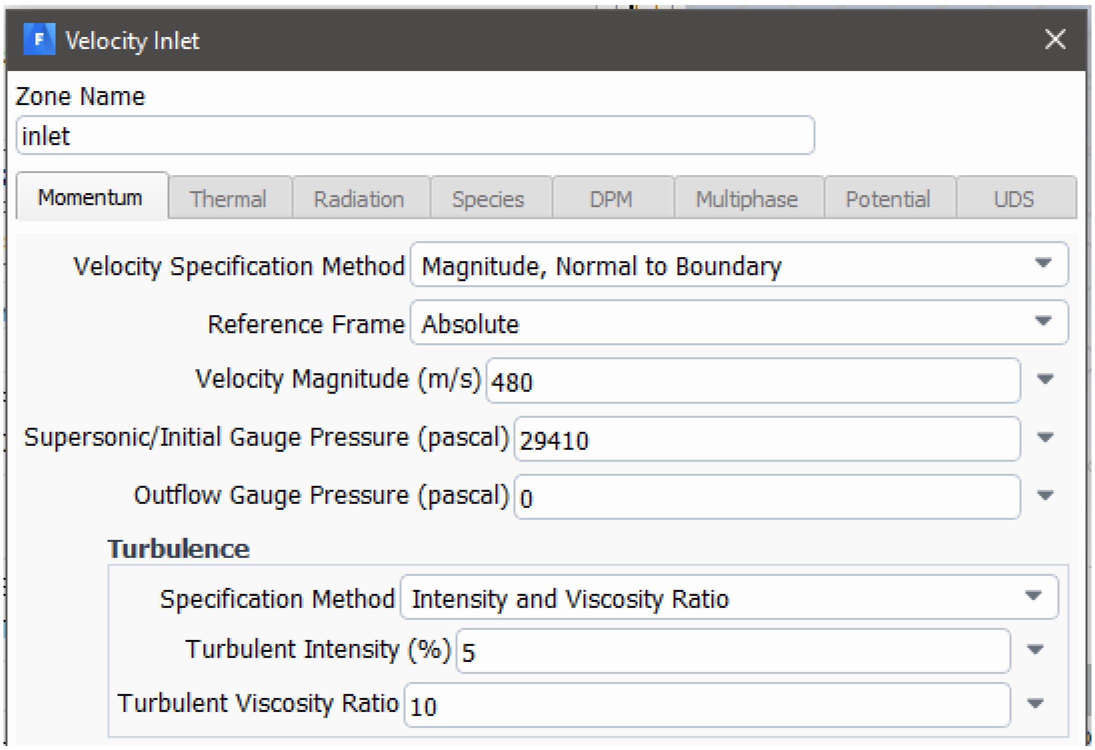


Figure 25: Velocity Inlet Conditions

- The method applied was **k-ω SST** since it is the best approach which works accurately at both near the wall and in the free stream.

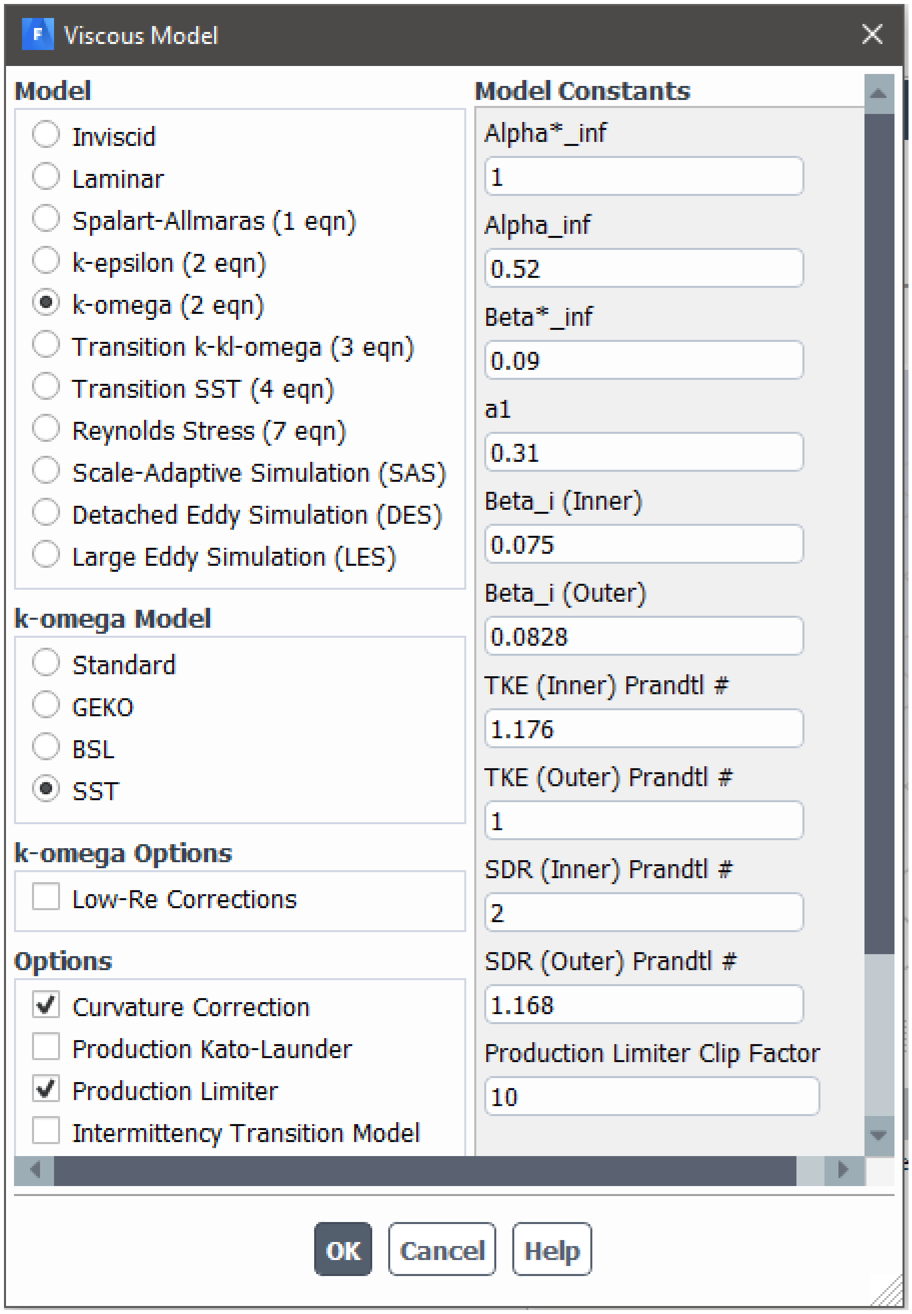


Figure 26: Viscous Model Conditions

- The solution method used was **second order upwind** scheme.

- **No slip shear condition** along with **stationary wall** was used on the walls/ surface of the rocket body.

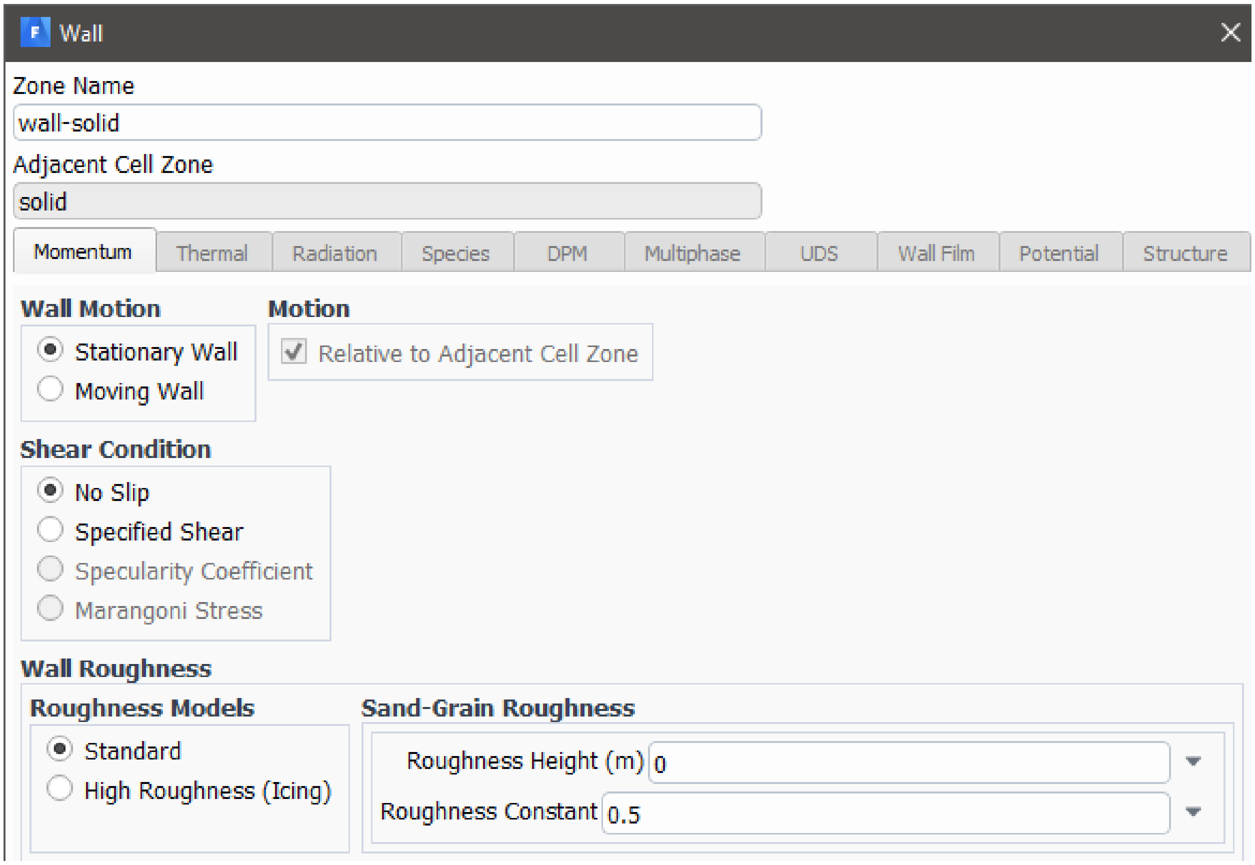


Figure 27: Wall Conditions

- The residuals were set to be **0.0001**
- The convergence condition was set to be when **all conditions are met** or in other words all the variables converge.
- The output parameters (**report definitions**) were set to be the **coefficient of lift ($C_l$)** and **coefficient of drag ($C_d$)**.

**Drag report:**

Drag coefficient was specified in Y- direction.

**Lift report:**

Lift coefficient was specified in Z- direction.

- **Reference values** were taken from the inlet.

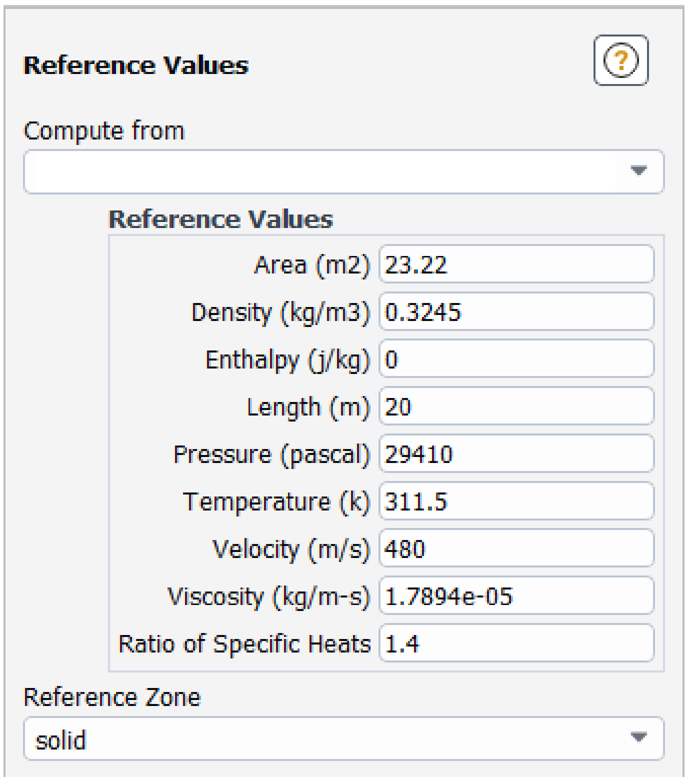


Figure 28: Reference Values

- **Standard initialization** was used for the simulation.
- The number of iterations was set as **1000 iterations** and the calculation was run.

## FEA Analysis:

The mesh is created on the rocket body with an element size of **0.1 m**. The generated mesh is displayed below.

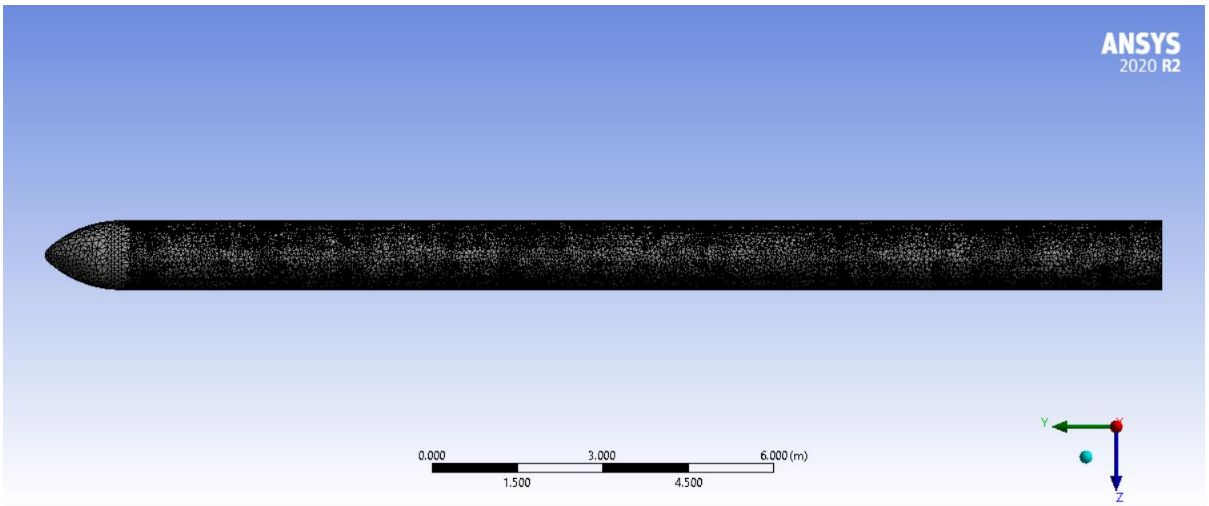


Figure 29: Structural Meshing

A finer mesh is created at and around the nose cone. The type of mesh was unstructured, and the shape of mesh elements used was triangular. The close-up view of meshing on the nose cone is shown:

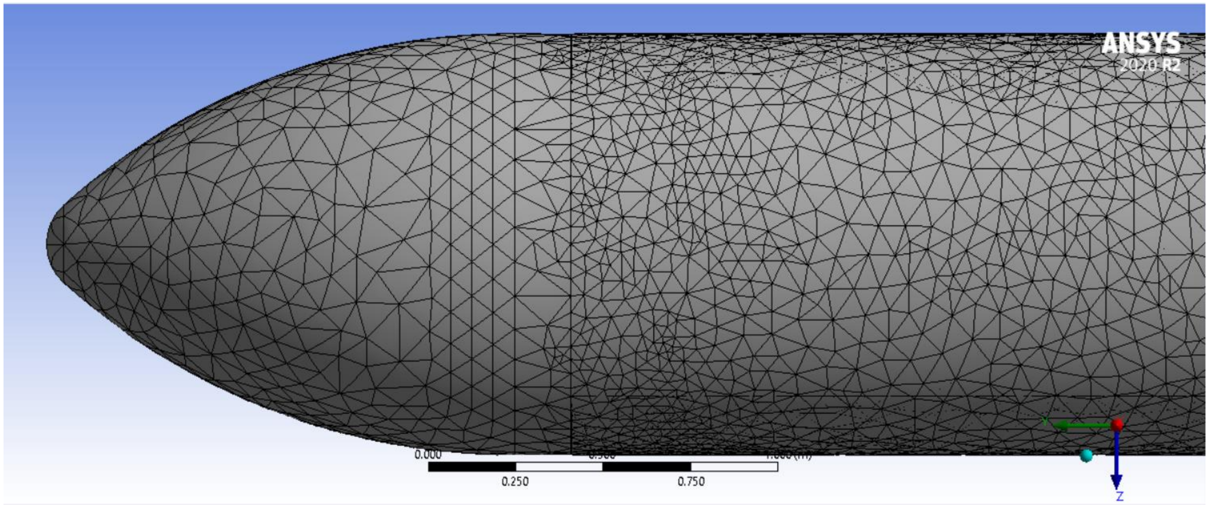


Figure 30: Close up view of Meshing

**Boundary Conditions:**

A fixed support was applied on the bottom end of the rocket. It was done to make sure that the rocket is held at a place and the external conditions like forces and pressures can be applied on them. In this way the obtained results will only show the values that are produced due to these applied conditions.

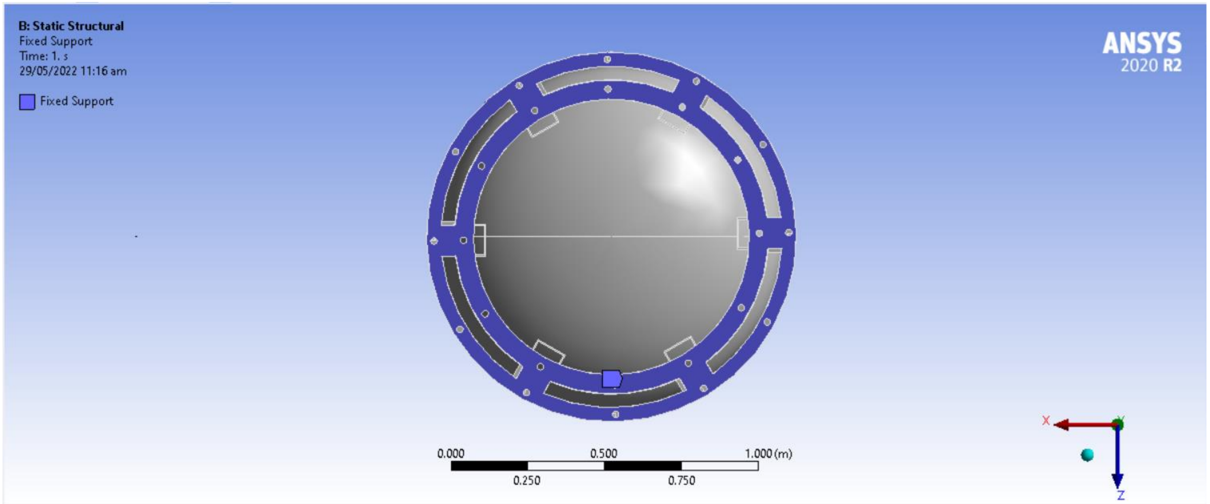


Figure 31: Fixed Support

**Applied Loads:**

Standard Earth gravity was applied to the rocket body for its close to realistic structural analysis through its flight. The value is 9.8066 m/s$^2$ and its direction is in the negative Y-axis as shown in figure.

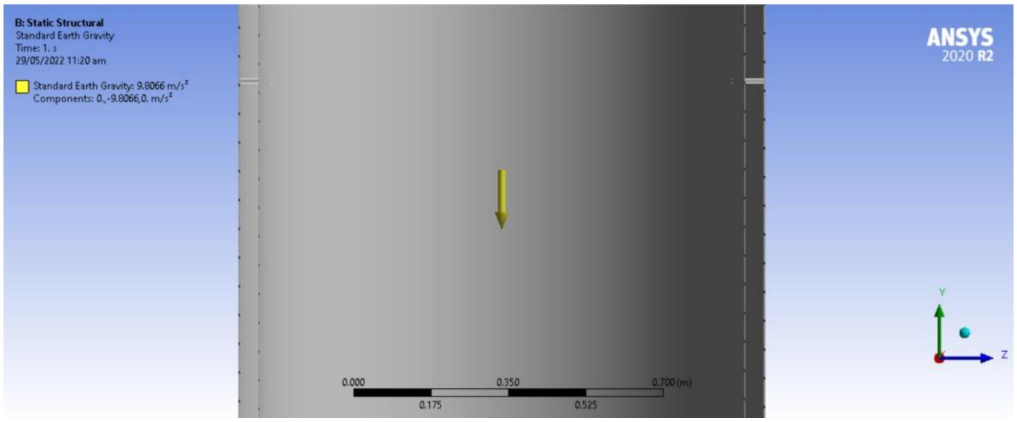


Figure 32: Standard Earth Gravity

All the four cylinders are pressurized vessels holding rocket fuel or oxygen. So, an internal pressure of 5 bar was applied inside the fuel tanks due to high pressure fuel filled in them.

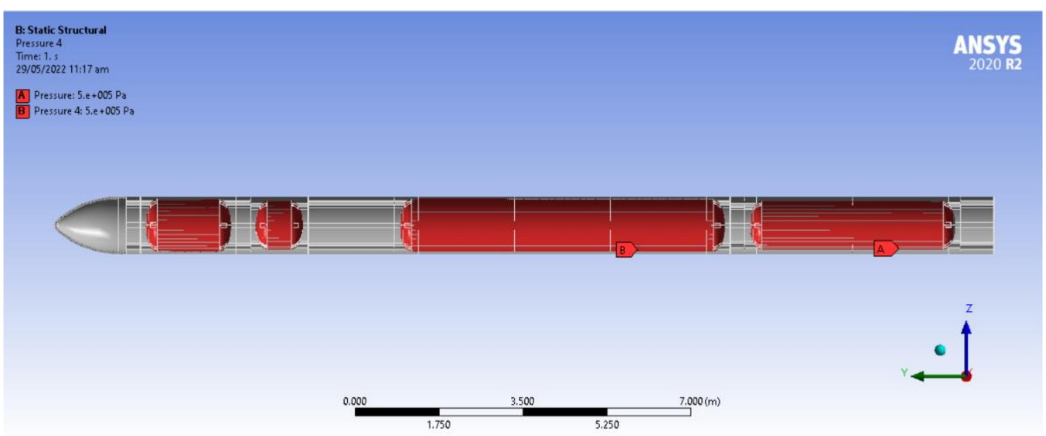


Figure 33: Cylinder Pressures

The external pressure was applied on the surface of the rocket body due to the flight conditions experienced by the rocket body. It is due to the external drag forces that are being applied on the surface in-flight. An external pressure of **71.1 kPa** was applied at the body surface.

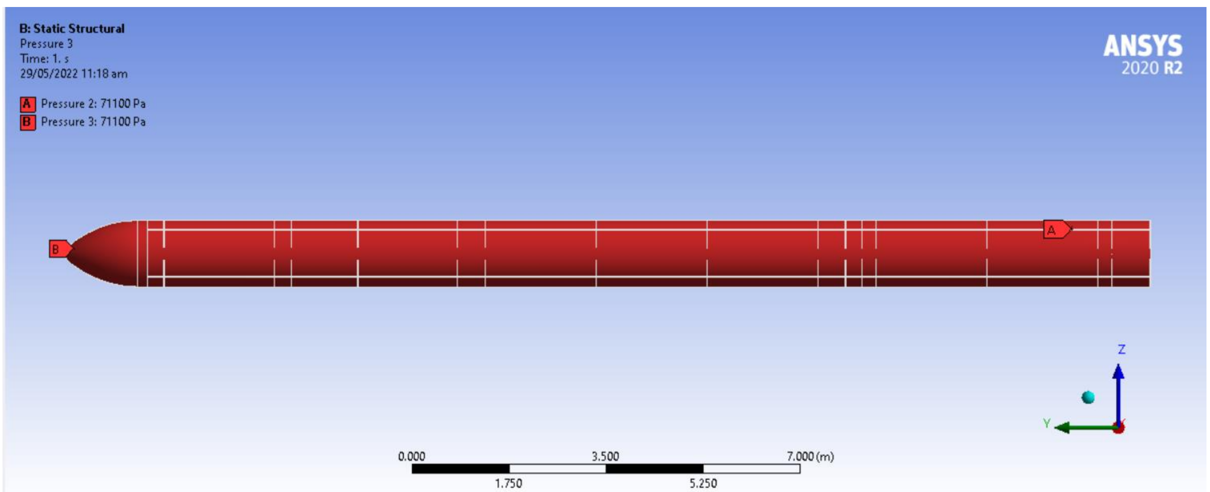


Figure 34: External Pressure

**Hydrostatic pressure:**

Hydrostatic pressure is applied considering the fuel tank is partially filled with fuel and the pressure increases downwards.

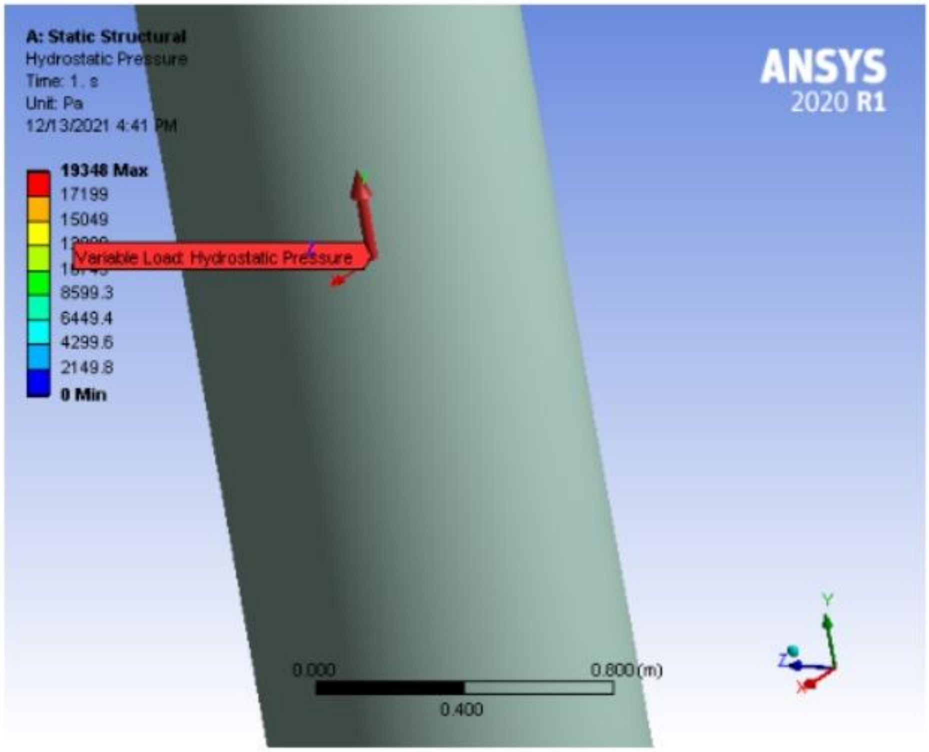


Figure 35: Hydrostatic Pressure

# CHAPTER 4: RESULTS AND DISCUSSIONS

## Computational Fluid Dynamics (CFD):

The simulation of scaled residuals is shown as follows:

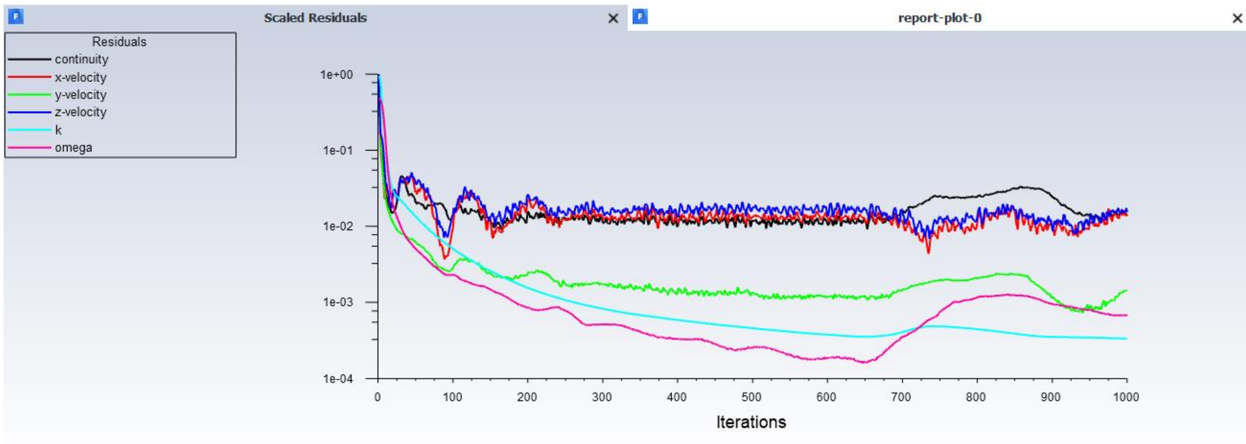


Figure 36: Scaled Residuals

The report plots of **coefficient of lift ($C_l$)** and **coefficient of drag ($C_d$)** in the simulation is shown as follows:

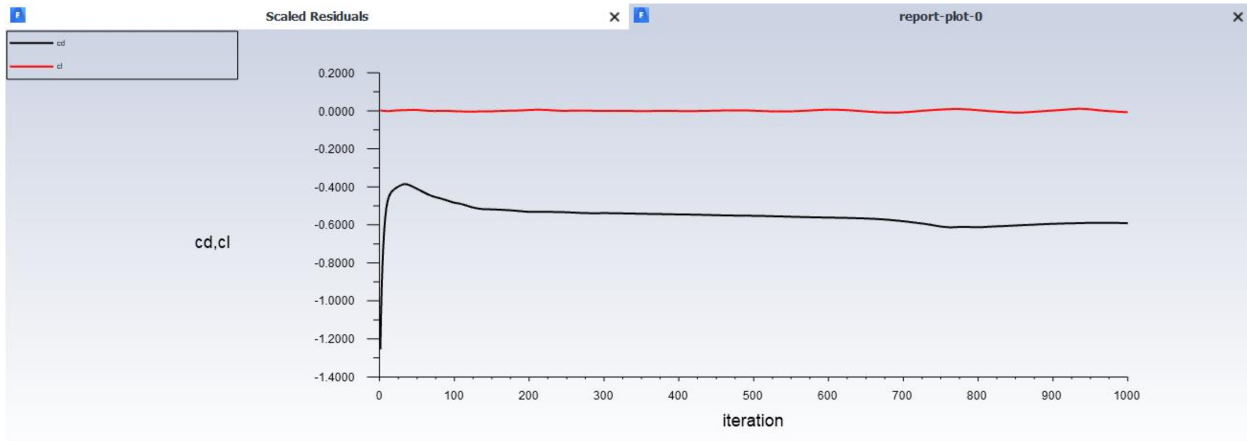


Figure 37: Report plots of coefficient of lift and coefficient of drag

The value of **coefficient of lift ($C_l$)** remains zero because the direction of the flow of air over the rocket body is normal to it.

The value of **coefficient of drag ($C_d$)** is almost **0.59**.

$$\textbf{Coefficient of lift } (\mathbf{C_l}) = \mathbf{0}$$

$$\textbf{Coefficient of drag } (\mathbf{C_d}) = \mathbf{0.59}$$

## Results for CFD:

After the simulation is completed, the results of the CFD analysis are plotted.

**Contour of Static Pressure:**

The **contour of static pressure** on the surface of the rocket is plotted and shown as follows:

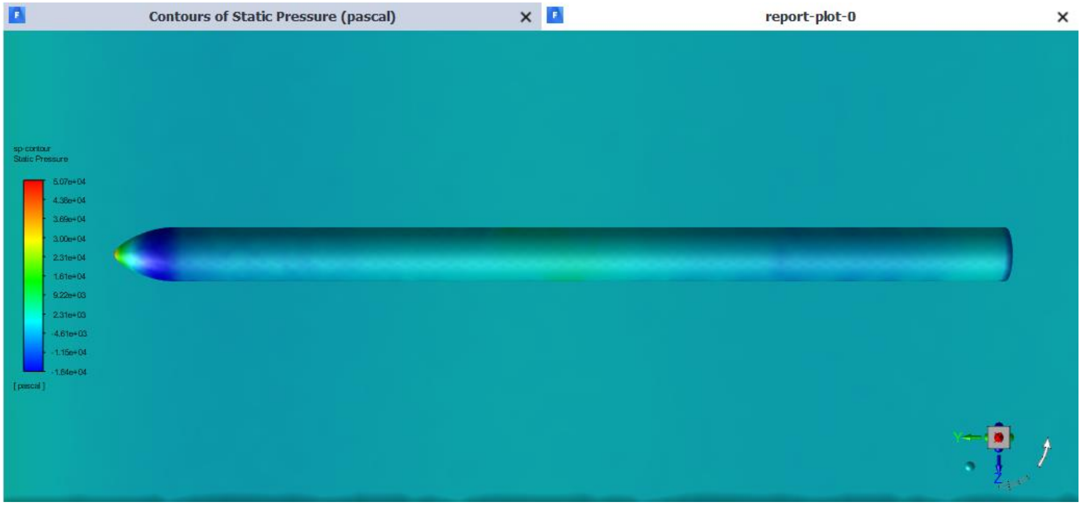


Figure 38: Contour of Static Pressure

The **close up or zoomed in view** of the **contour of static pressure** at the nose cone of the rocket is shown as follows:

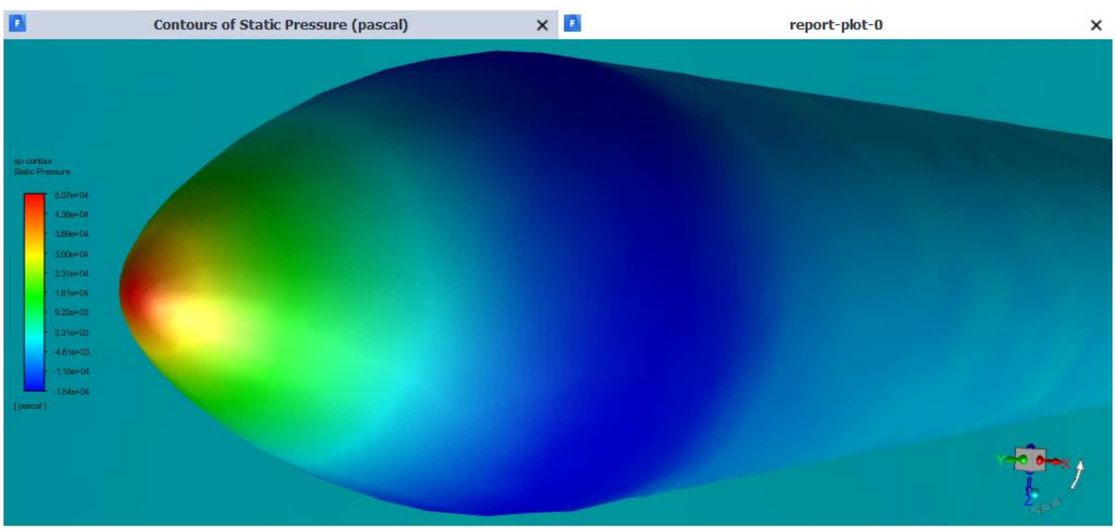


Figure 39: Close up view of contour of static pressure

The **maximum static pressure** occurs at the **tip** of the nose cone of the rocket and its value is **50700 Pa** or **50.7 kPa**.

**Contour of Dynamic Pressure:**

The **contour of dynamic pressure** on the surface of the rocket is plotted and shown as follows:

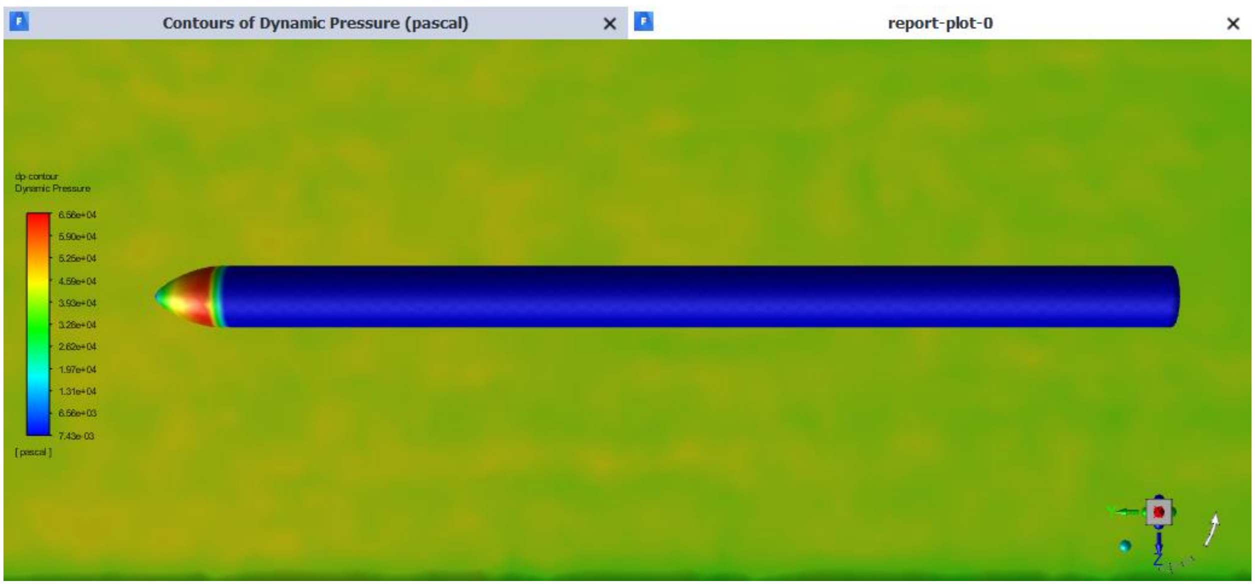


Figure 40: Contours of Dynamic Pressure

The **close up or zoomed in view** of the **contour of dynamic pressure** at the nose cone of the rocket is shown as follows:

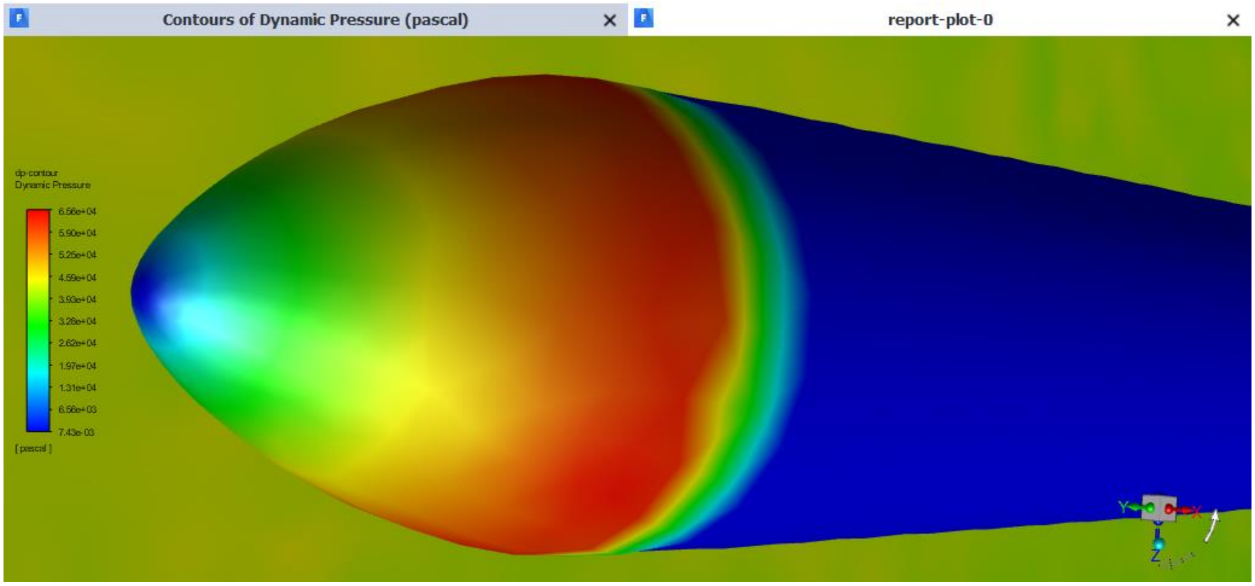


Figure 41; Close up view of Contours of Dynamic Pressure

It can be noticed that the **minimum dynamic pressure** occurs at the **tip** of the nose cone of the rocket because the magnitude of the velocity approaches to **zero** at that point.

The **maximum dynamic pressure** occurs at around the **outer edges** of the nose cone of the rocket and its value is **65600 Pa** or **65.6 kPa**.

**Contour of Total Pressure:**

The **contour of total pressure** on the surface of the rocket is plotted and shown as follows:

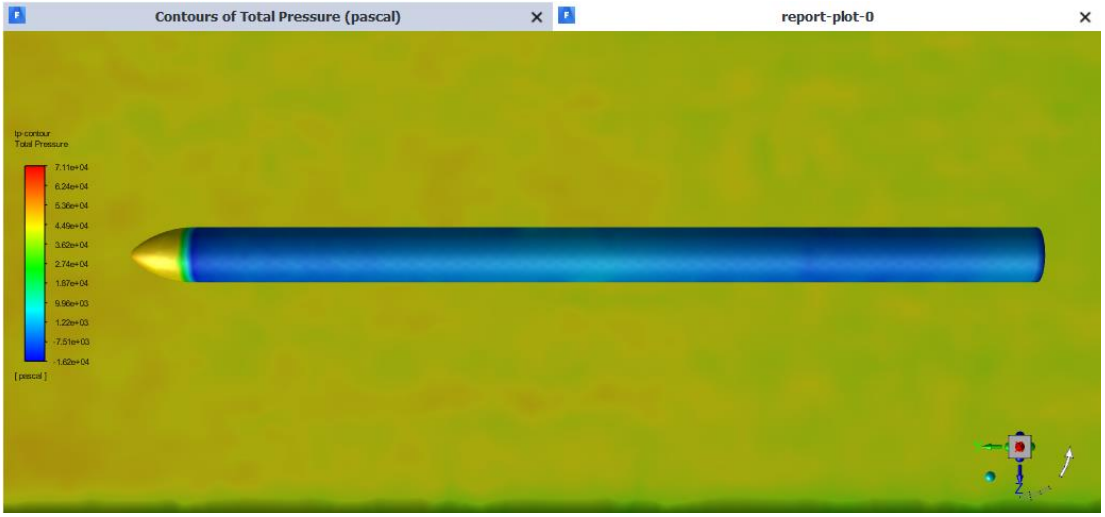


Figure 42: Contour of Total Pressure

The **close up or zoomed in view** of the **contour of total pressure** at the nose cone of the rocket is shown as follows:

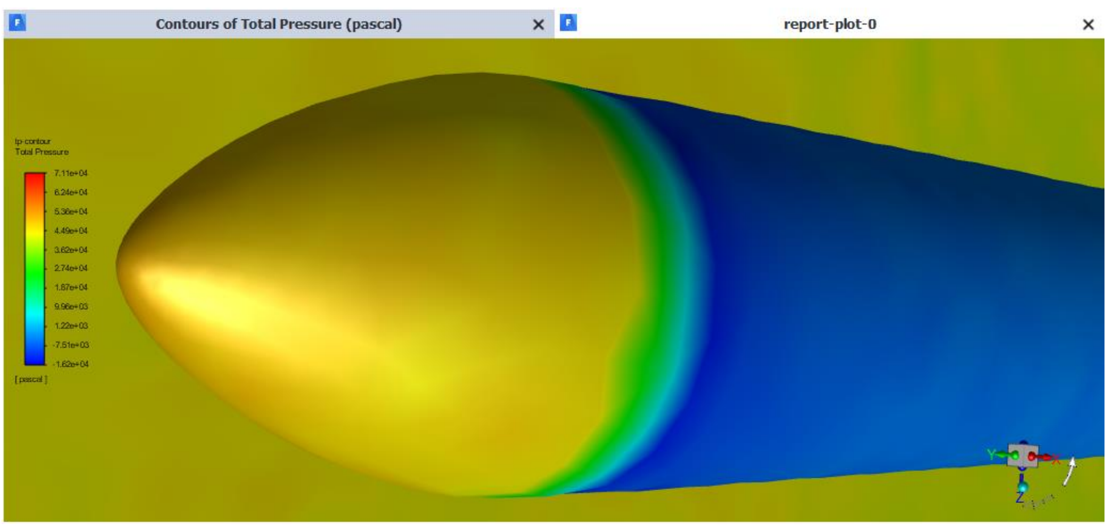


Figure 43: Close up view of Contour of Total Pressure

The **maximum total pressure** occurs almost at the **tip** of the nose cone of the rocket and its value is **71100 Pa** or **71.1 kPa**.

**Contour of Pressure Coefficient:**

The **contour of pressure coefficient** on the surface of the rocket is plotted and shown as follows:

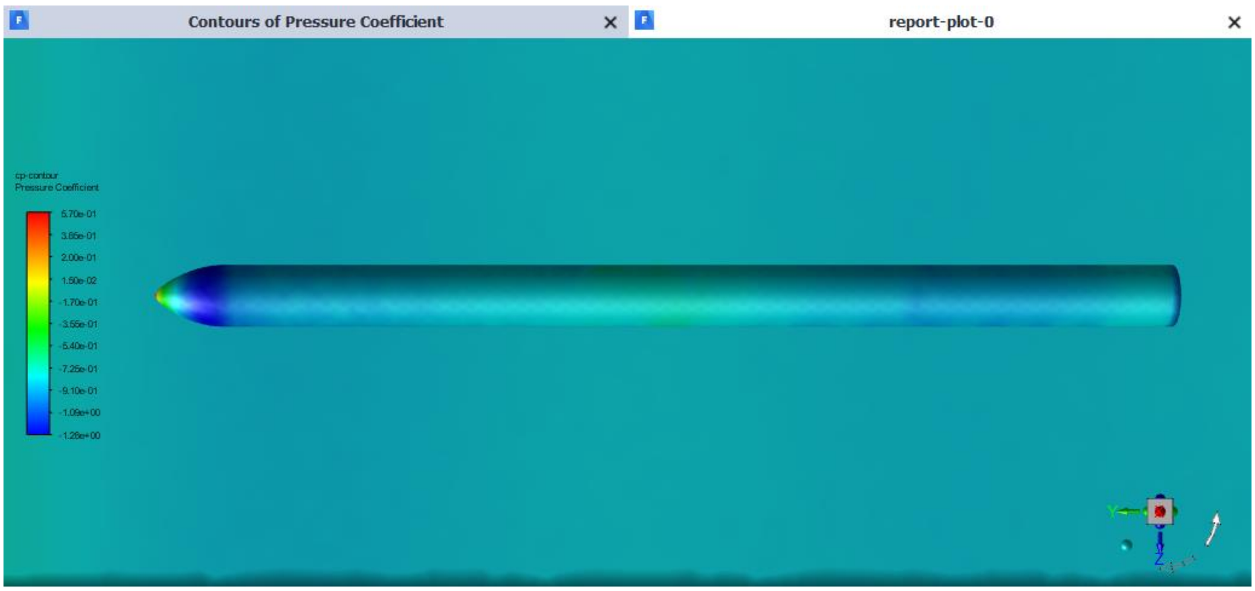


Figure 44: Contour of Pressure Coefficient:

The **close up or zoomed in view** of the **contour of pressure coefficient** at the nose cone of the rocket is shown as follows:

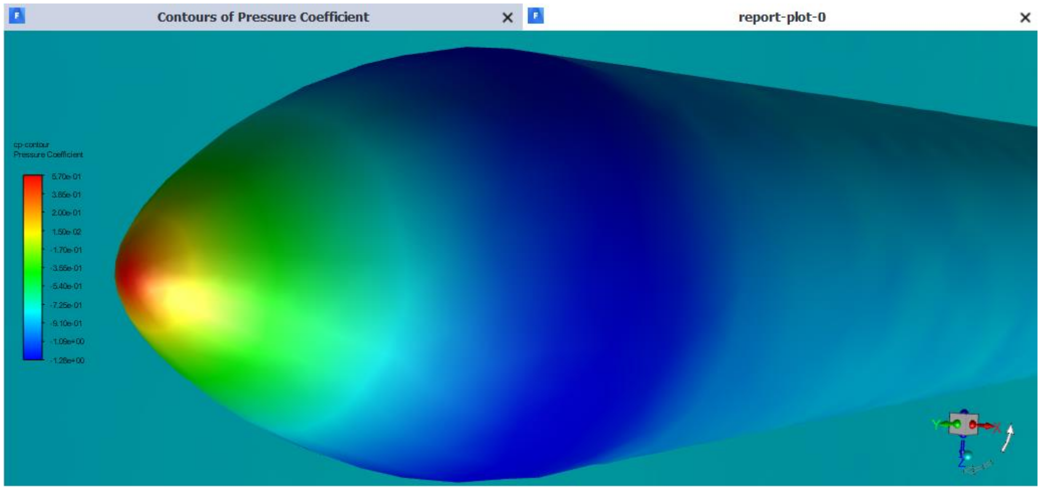


Figure 45: Close up view of Contour of Pressure Coefficient

The **maximum pressure coefficient** occurs at the **tip** of the nose cone of the rocket and its value is **0.57**.

**Plot of Pressure Coefficient:**

The **plot of pressure coefficient** on the surface of the rocket is plotted and shown as follows:

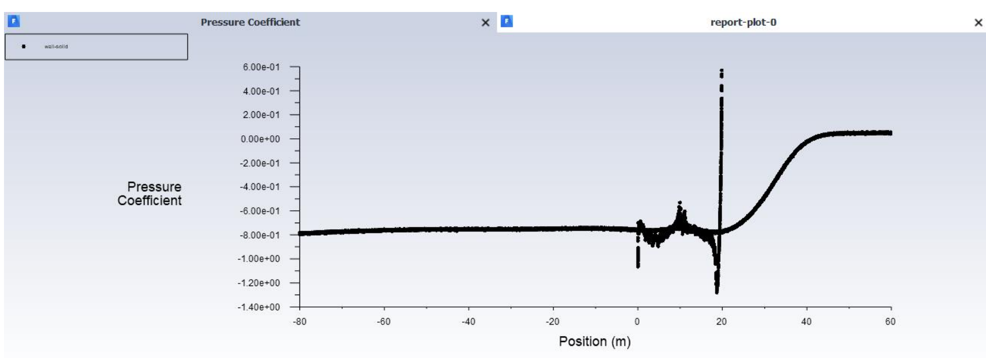


Figure 46: Pressure Coefficient Plot

The variation of the pressure coefficient in the direction of the air flow along the length of the rocket is displayed.

When the air begins to flow at the starting point of the flow domain, the value of the pressure coefficient is zero since there is no change at the start.

When the air reaches the tip of the nose cone, an adverse pressure gradient occurs, and the pressure coefficient suddenly comes down to around **0.8** while moving around the curvature of the nose cone.

When the air leaves the body of the rocket from its trailing edge, it maintains the pressure coefficient of around **0.8** throughout the wake region of the flow.

In this way, the situation of pressure at any point of the whole flow domain can be evaluated using these plots.

## Finite Element Analysis (Fuel Tank):

### Hydrostatic pressure:

The study is run to check the hydrostatic pressure that increases downwards, the results are shown in the figure below. The maximum hydrostatic pressure is at the bottom which is 19.348 kPa.

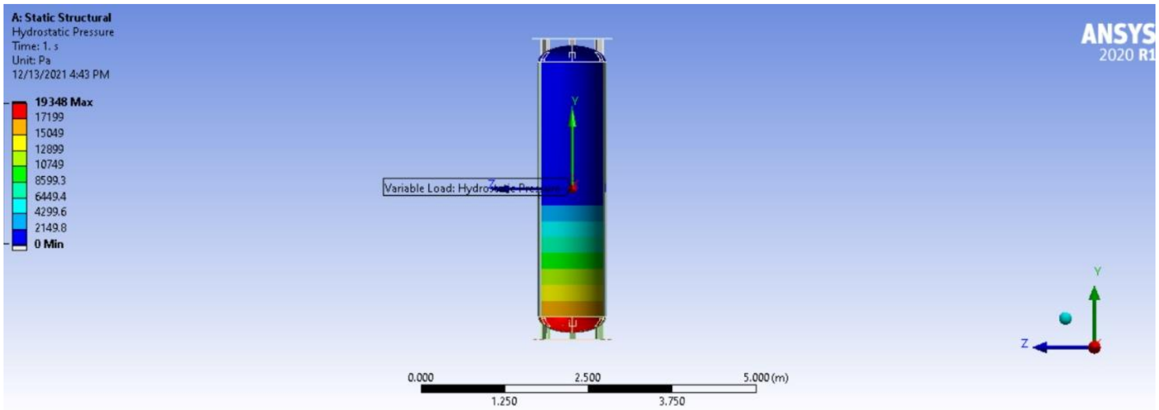


Figure 47: Hydrostatic Pressure result

**Complete Body:**

The results of the FEA analysis are shown below.

The **von-Mises stress** is evaluated on the rocket body. The maximum value of von-Mises stress that occurs on it is **164.14 MPa**.

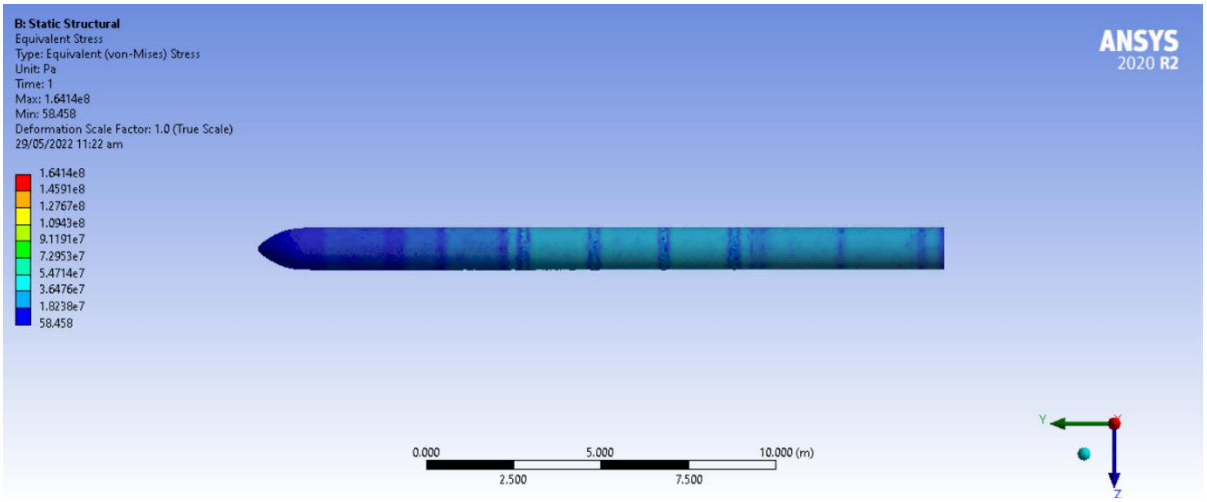


Figure 48: Von Mises Stress

The stress is shown in the **sectioned view** where it is noticed that the maximum stress occurs at the pressurized cylinders. It is because highly pressurized fuel is present inside them.

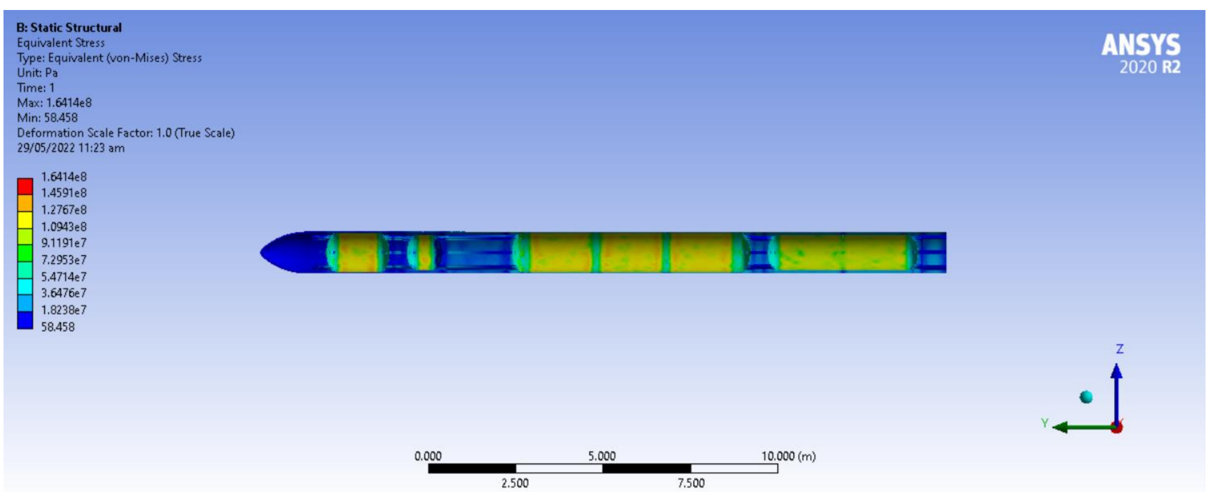


Figure 49: Von Mises Stress Sectioned View

The **elastic strain** is that is produced in the body because of the stress is shown below. The maximum value of elastic strain that occurs in it is **0.0026148**.

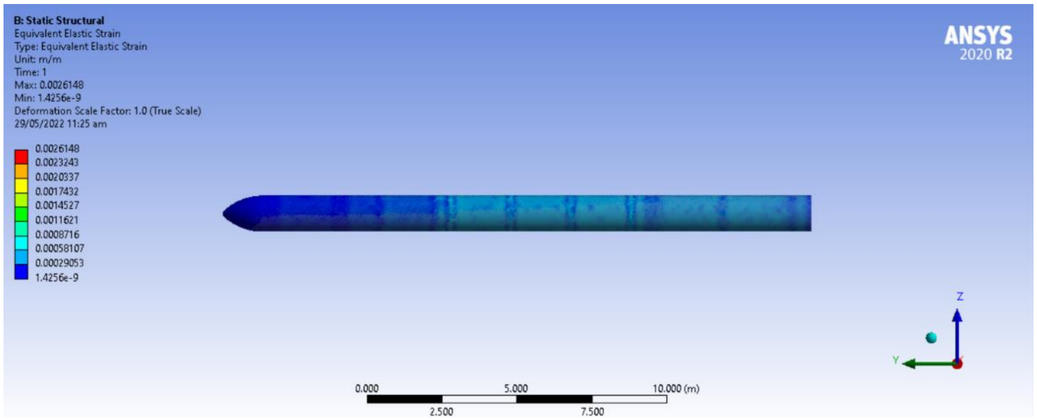


Figure 50: Elastic Strain

The strain is shown in the **sectioned view** where it is noticed that the maximum stress occurs at the pressurized cylinders. It is because the maximum stress is applied at this position, so the resultant maximum strain also occurs here.

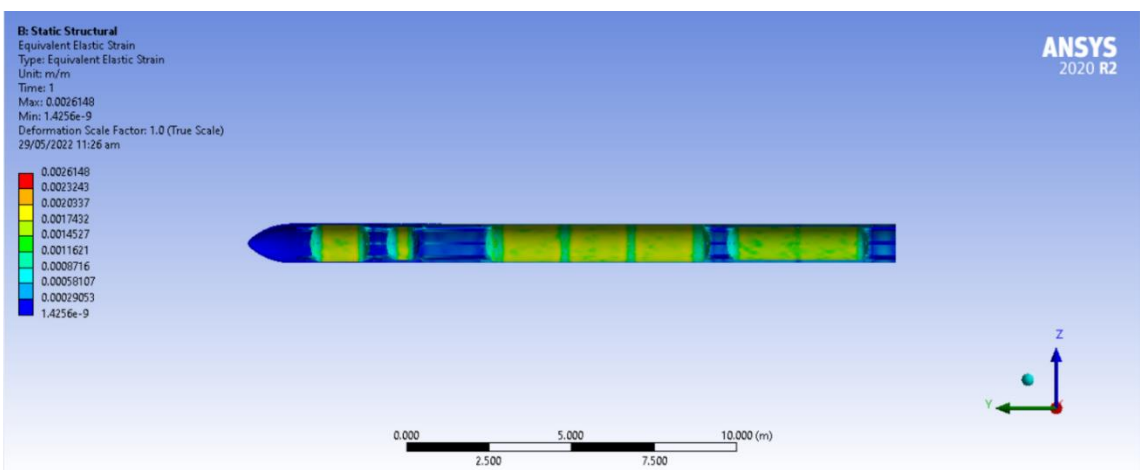


Figure 51: Elastic Strain Sectioned View

The **total deformation** that is produced in the body because of the applied stress conditions is shown below. The maximum value of total deformation that occurs in it is **7.5184mm**. This value is almost negligible if we compare it to the overall body of the rocket.

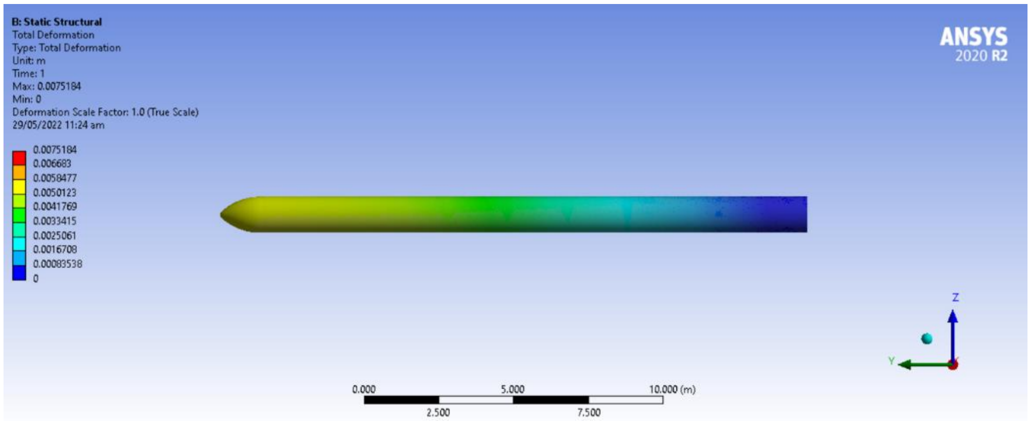


Figure 52: Total Deformation

The total deformation is shown in the **sectioned view** where it is noticed that the maximum total deformation occurs at the points near the nose cone. It is because this is the farthest point from the fixed support so there occurs the maximum deformation.

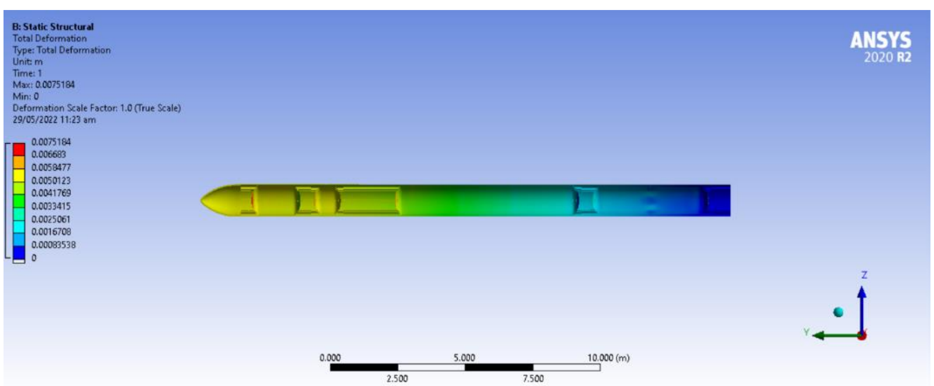


Figure 53: Total Deformation Sectioned View

**Factor of safety**

The factor of safety can be calculated by using the following formula:

$$FOS = \frac{\sigma_Y}{\sigma_A}$$

Here, the maximum applied stress is **164.14MPa** and the yield strength of Aluminium T6-6061 is **240MPa.** So, the factor of safety can be calculated as below:

$$FOS = \frac{276}{164.14}$$

$$FOS = 1.68$$

The factor of safety is very realist because in most real-life scenarios a FOS of above 1.4 is being used.

# CHAPTER 5: CONCLUSION AND RECOMMENDATION

## Conclusion:

We completed the whole structural analysis of the satellite launch vehicle to check its response during in-flight conditions. First the computational fluid dynamics (CFD) analysis of the rocket was performed while applying the max Q (maximum dynamic pressure) conditions on the rocket body. The input parameters were entered in the setup of the simulation and the calculation was run in order to obtain the results like static pressure, dynamic pressure, total pressure, and pressure coefficient. The output reports generated were of coefficient of lift ($C_l$) and coefficient of drag ($C_d$).

The value of **coefficient of lift ($C_l$)** is **zero** because the direction of flow is normal to the boundary of the flow domain and along the axis of the rocket length. The value of **coefficient of drag ($C_d$)** is **0.59** which is close to the values found in literature which are 0.60 so our design is acceptable and also has **improved** drag coefficient.

The vehicle was analyzed, and the points were noted on the body where there are maximum stresses. The values of the maximum static, dynamic and total pressures were evaluated and then used further for FEA analysis. The value of maximum total pressure was **71.1 kPa**. This value was imported for the Static Structural analysis in ANSYS and the simulation was performed according to it.

In the FEA analysis, the mesh of the rocket body was generated first and then for the analysis, the input conditions are applied on the rocket. The internal pressure of **5 bar** was applied in the fuel tanks and an external pressure of **71.1 kPa** was applied on the surface of the rocket. The simulation was performed in order to achieve the desired results. The results have shown that the maximum von-Mises stress occurred in the rocket is **164.14 MPa** which is well below the yield strength of our material used (Aluminum T6 6061) whose strength is **280 MPa**.

In this way, a factor of safety of around **1.68** is achieved which is an acceptable value practically. Hence, our design of satellite launch vehicle is accepted, and our structural analysis is successful.

## Recommendations:

- There was only flow analysis and static structural analysis performed but in such supersonic conditions, the temperature of the fluid (air) and the surface of the body also changes and they get hotter. Due to this, the pressures and the strength of the material may also change which can cause in deviation of results. To overcome this issue, the thermal analysis should also be included in the complete analysis of the rocket so that we can get closer to the actual conditions and achieve more accurate results.
- When a rocket is in-flight, it also experiences harmonic forces which cause vibration in the whole rocket body and if the harmonic frequency is close to the natural frequency of the vehicle, there will be resonance that will cause in instability of the rocket and there can be disastrous failure. So, it is quite necessary to also include the vibrational analysis while performing the complete

analysis of our satellite launch vehicle to avoid any failure due to resonance or unwanted vibrations.

- Our whole structural analysis was computational based and was performed on the software ANSYS. Although we obtained quite accurate results and our analysis was acceptable but before using this system in the practical field for aerospace applications, there should also be performed a laboratory test to make sure that it is valid practically. For this purpose, a wind tunnel test should be done after this computational analysis.

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# APPENDIX I: DRAWINGS OF THE MODEL PARTS

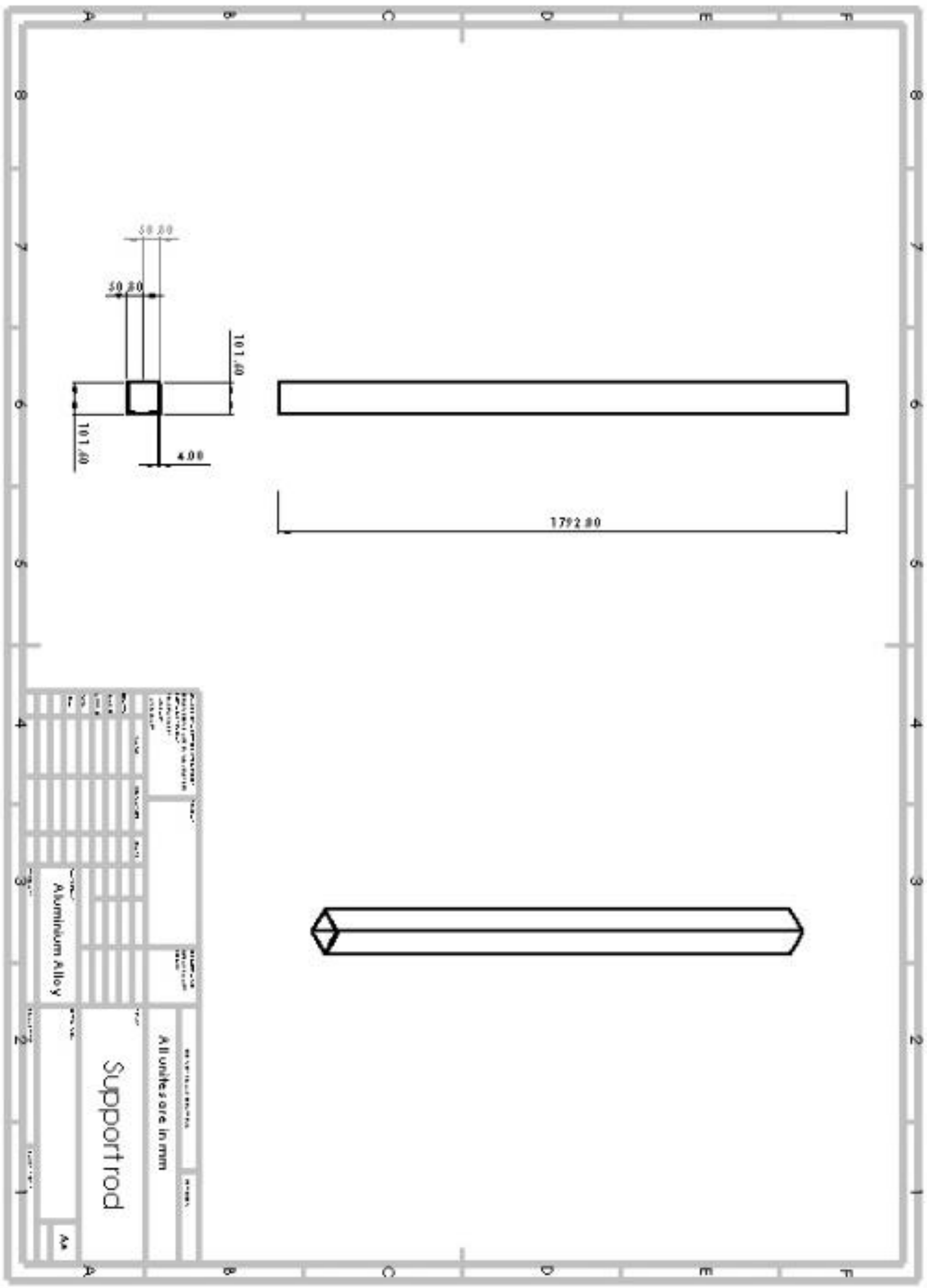


Figure 54: Support Rod Drawing

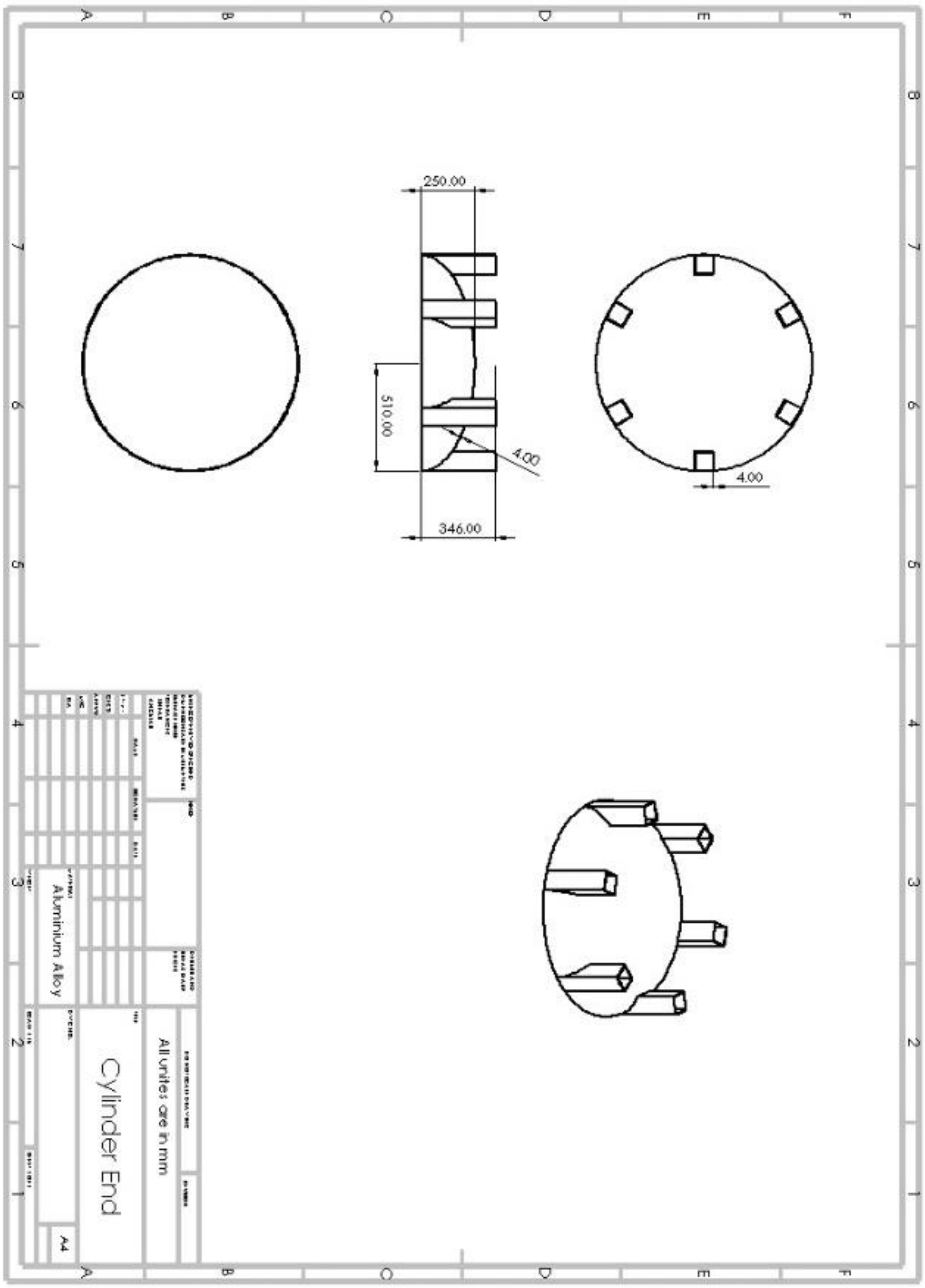


Figure 55: Cylinder End Drawing

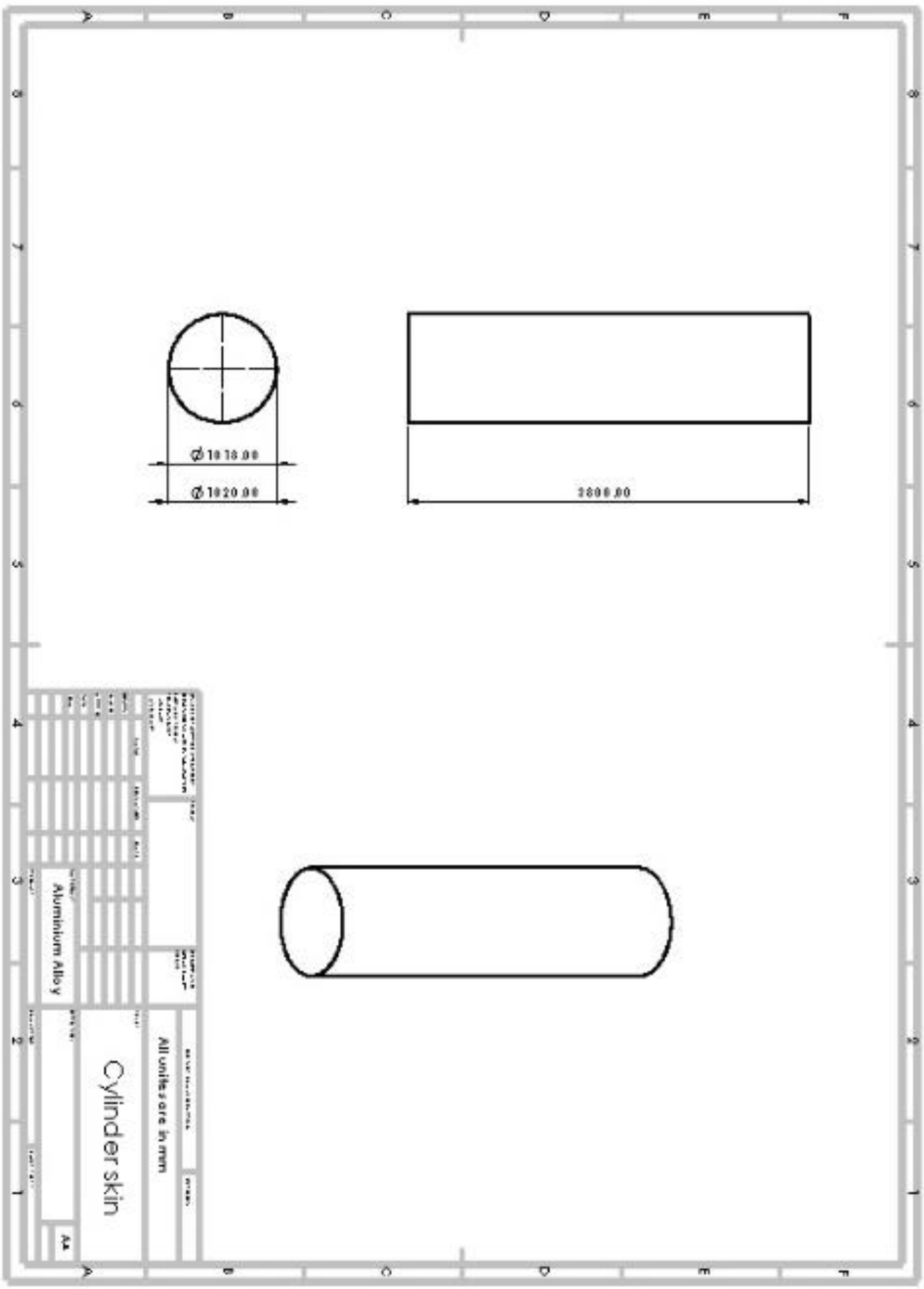


Figure 56: Cylinder Skin Drawing

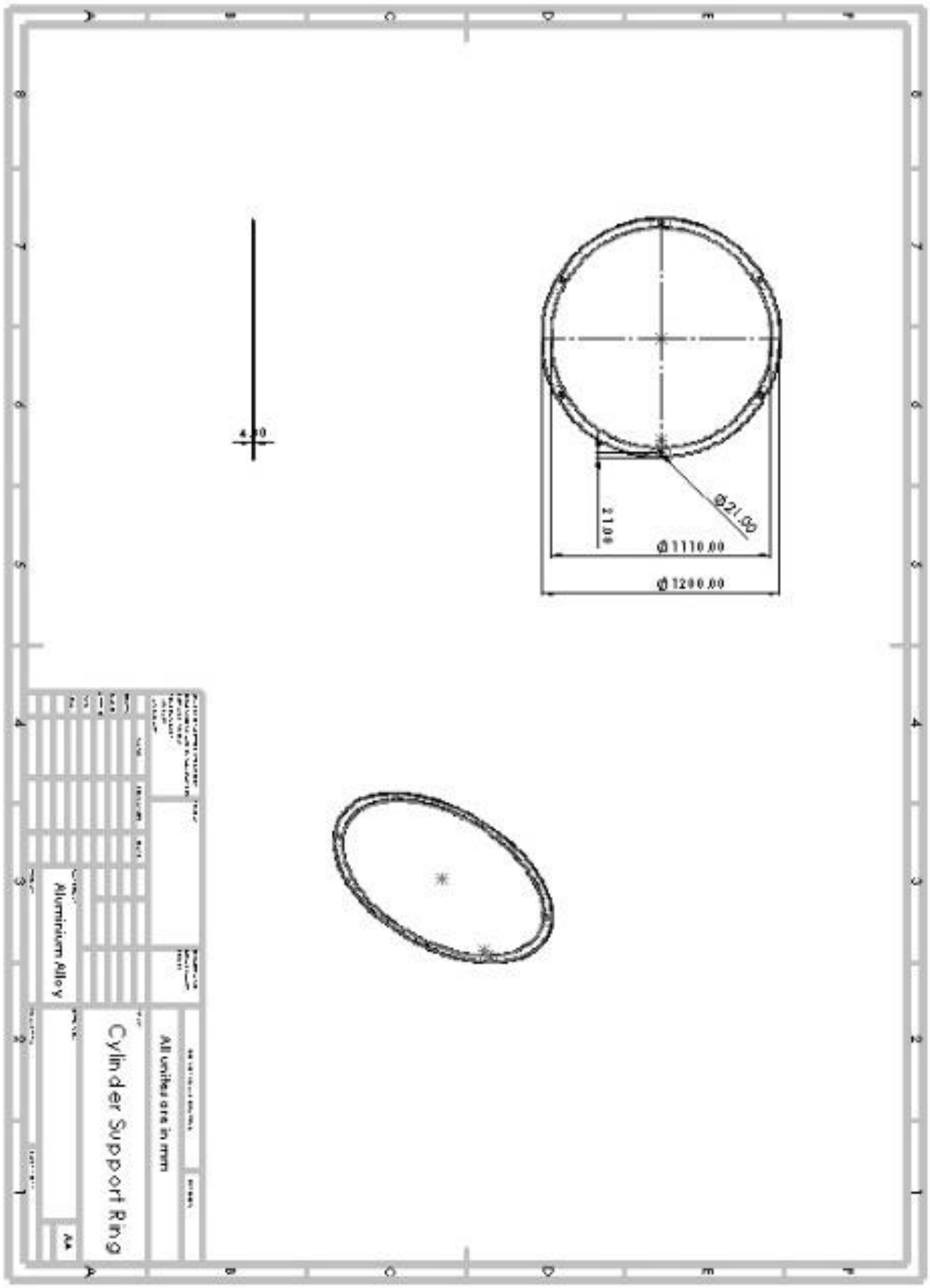


Figure 57: Cylinder Support Ring

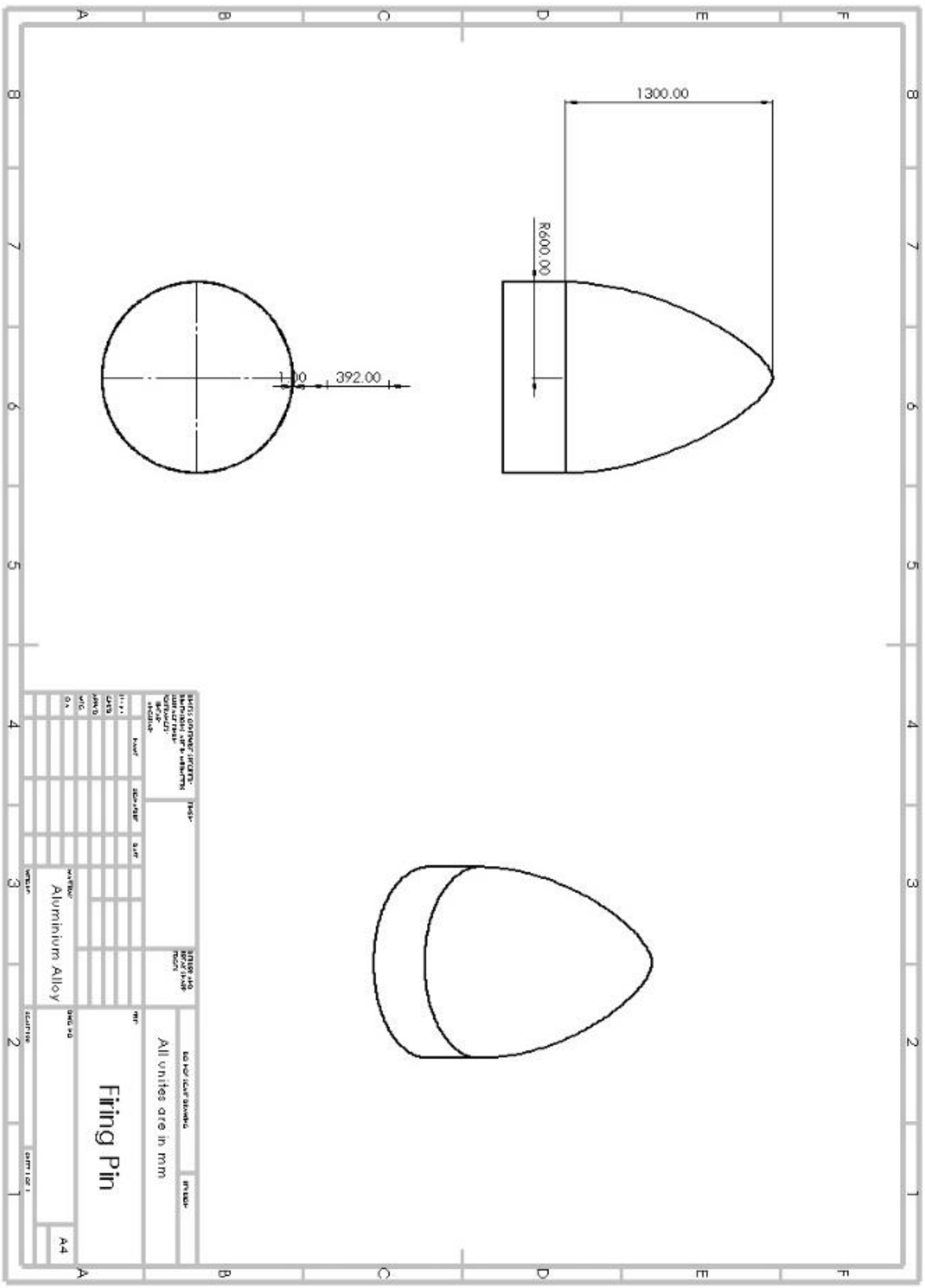


Figure 58: Firing Pin Drawing

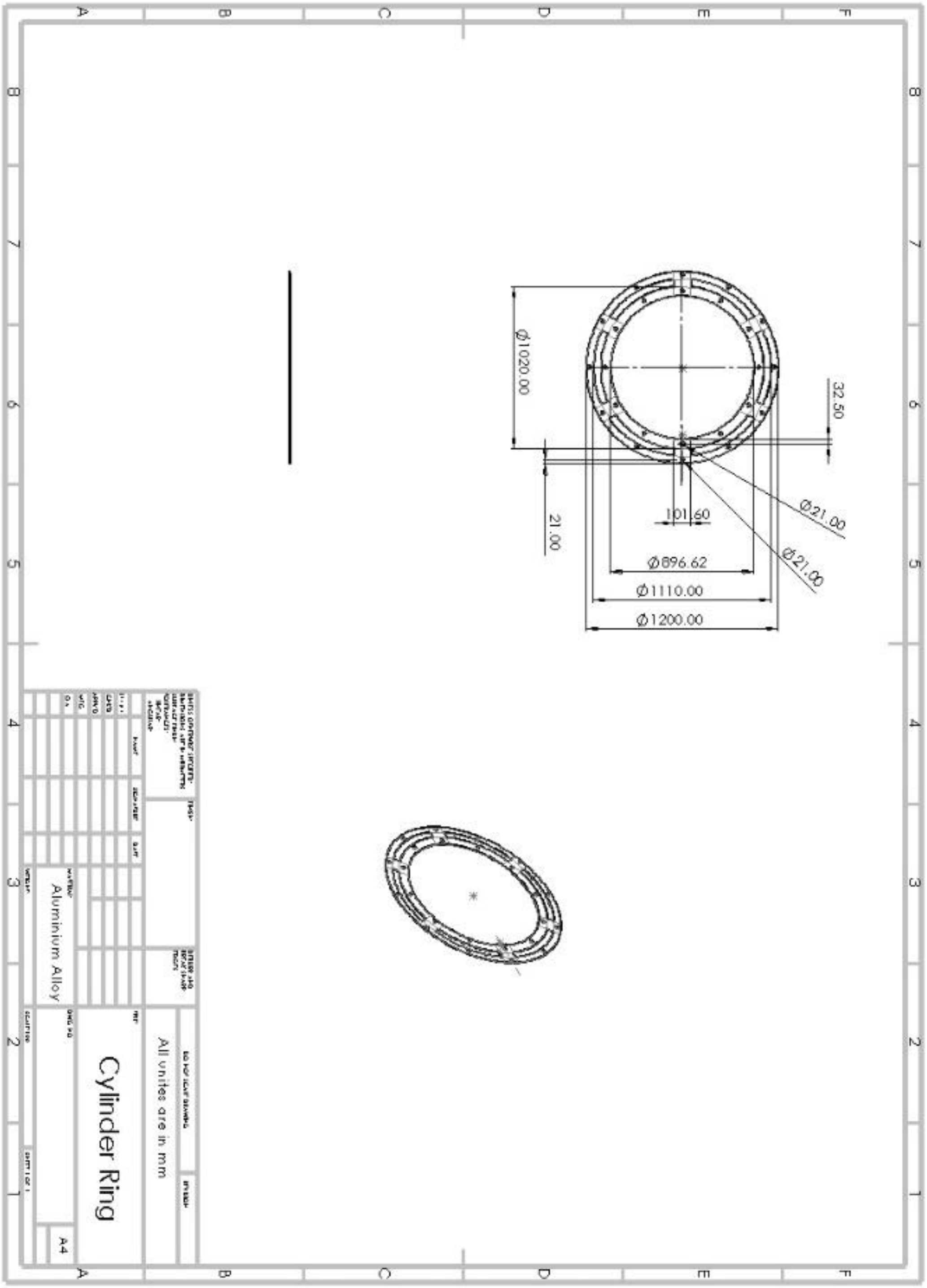


Figure 59: Cylinder Ring Drawing

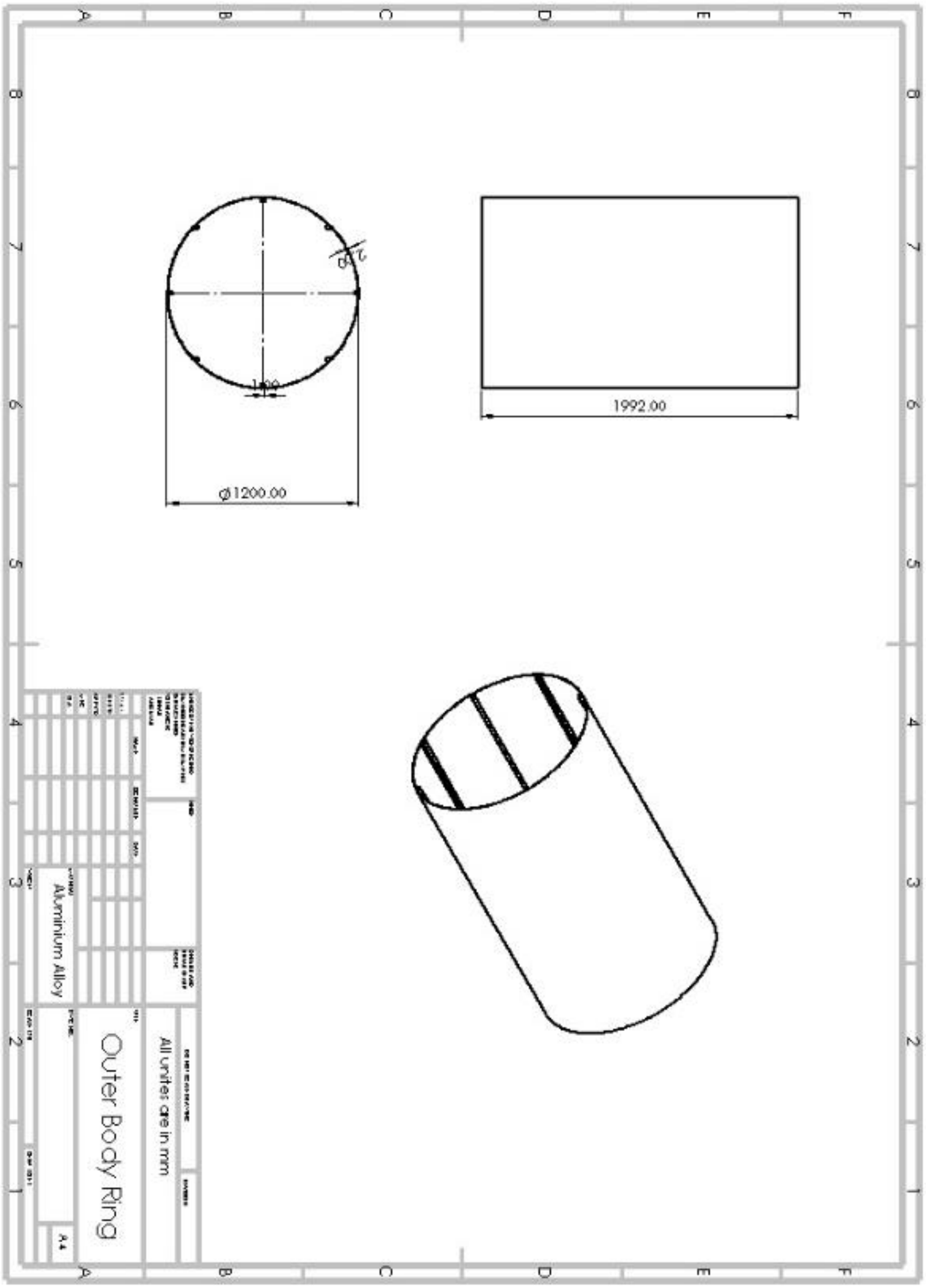


Figure 60: Outer Body Ring