

Creep Analysis of a Hollow Cylindrical Shell

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Abstract:

Creep, a time-dependent deformation phenomenon occurring under constant stress and elevated temperatures, is a critical consideration in materials engineering, particularly for applications involving high temperatures such as power generation, aerospace, and structural components. This document provides a comprehensive exploration of creep behavior, focusing on its stages (primary, secondary, and tertiary), underlying mechanisms, and mathematical modeling. Key creep models, including Norton's Power Law and the Dorn Equation, are discussed, emphasizing the role of material constants (C_1, C_2, C_3, C_4) in predicting creep strain rates and deformation.

A detailed case study is presented, focusing on the creep analysis of a hollow structural steel cylinder with fixed inner and outer diameters but varying length ratios, subjected to internal pressure and high temperatures. Using ANSYS Workbench, the study employs Norton's Power Law to model creep deformation, calculating radial displacement, axial elongation, and creep strain over time. The methodology includes geometry creation, material property definition, loading conditions, and boundary constraints, providing a practical framework for evaluating creep in engineering applications. The experiment investigates how different length-to-diameter ratios influence creep behavior, offering insights into the design and optimization of cylindrical structures under sustained stress.

Keywords

Creep analysis, Hollow cylinder, Finite element analysis,

1. INTRODUCTION

Creep, known also as cold flow, is the permanent deformation that increases with time under constant load or stress. It results due to long time exposure to large external mechanical stress within limit of yielding and is more severe in material that are subjected to heat for long time. The rate of deformation is a function of the material's properties, exposure time, exposure thermodynamics/thermodynamic-properties/what-is-temperature-physics'' temperature and the applied structural load. Creep is a very important phenomenon if we are using materials at high temperature. Creep is very important in power industry and it is of the highest importance in designing of jet engines. For many relatively short-life creep situations (e.g. turbine blades in military aircraft), time to rupture is the dominant design consideration. Of course, for its determination, creep tests must be conducted to the point of failure; these are termed creep rupture tests.

Creep becomes a problem when the stress intensity is approaching the fracture failure strength. If the creep rate increases rapidly, the strain becomes so large that it could result in failure. The creep rate is controlled by minimizing the stress and temperature of a material. Creep is more severe in materials that are subjected to heat for long periods and generally increases as they near their melting point. It is observed in all materials types; for metals, it becomes important only for temperatures greater than about $0.4T_m$, where T_m is the absolute melting temperature.

For example, creep caused failure is an important failure mode of turbine blades of an aircraft engine. In this case, a turbine blade will cause the blade to contact the casing, resulting in the failure of the blade and the engine.

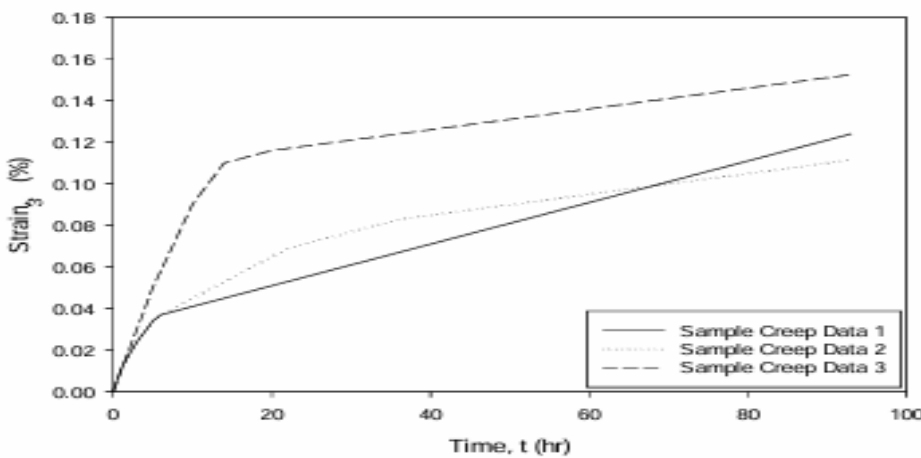
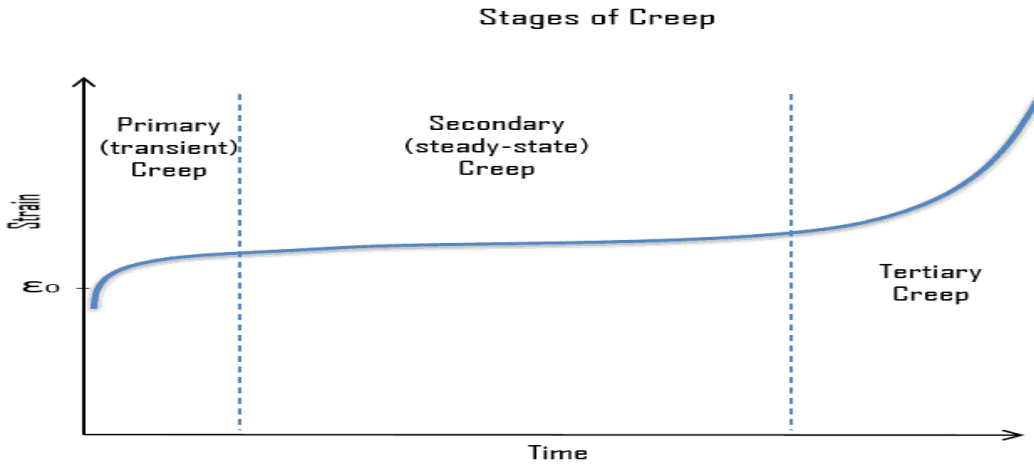


Figure 1: Examples of primary and secondary dominant creep.

The Norton power law is expressed mathematically as:

$$\dot{\epsilon} = A\sigma^n e^{-\frac{Q}{RT}}$$

where:

- $\dot{\epsilon}$ is the steady-state creep strain rate (s^{-1}),
- σ is the applied stress (Pa),
- A is a material-dependent constant (depends on microstructure and mechanism),
- n is the stress exponent (dimensionless, indicates creep mechanism),
- Q is the activation energy for creep (J/mol),
- R is the universal gas constant (8.314 J/mol·K),
- T is the absolute temperature (K).

Simplified Form (Isothermal Conditions):

If temperature is constant, the equation reduces to:

$$\dot{\epsilon} = A'\sigma^n$$

where $A' = Ae^{-\frac{Q}{RT}}$ is a temperature-dependent constant.

Interpretation:

- $n = 1$: Diffusion-controlled creep (viscous flow, Newtonian behavior).

- $n \approx 3 - 5$: Dislocation creep (power-law creep).
- $n > 5$: Higher stress regimes or other mechanisms.

This law is widely used in metallurgy, geology, and high-temperature engineering to model creep behavior in metals, ceramics, and polymers.

OBJECTIVE :

The objective of this analysis is to evaluate the creep behavior of a hollow structural steel cylinder under sustained loads using the power creep law constants.

MATERIAL PROPERTIES :

Mechanical Properties

- Young's Modulus (E): 210 GPa (30,000,000 psi)
- Poisson's Ratio (ν): 0.3
- Yield Strength (σ_y): 250-350 MPa (36,000-50,000 psi)
- Ultimate Tensile Strength (σ_u): 400-600 MPa (58,000-87,000 psi)
- Elongation at Break (ϵ): 20-30%

Thermal Properties

- Thermal Conductivity (k): 50-60 W/mK (35-42 Btu/hft²°F)
- Specific Heat Capacity (c): 500-600 J/kgK (0.12-0.14 Btu/lb°F)
- Thermal Expansion Coefficient (α): $12-15 \times 10^{-6} \text{ K}^{-1}$ ($6.7-8.3 \times 10^{-6} \text{ }^\circ\text{F}^{-1}$)

Creep Properties

- Creep Constant (A): 1.0×10^{-10} (1/s)
- Stress Exponent (n): 3.5
- Time Exponent (m): 0.5

Other Properties

- Density (ρ): 7850 kg/m³ (490 lb/ft³)
- Corrosion Resistance: Moderate to high, depending on the specific alloy and environmental conditions.

Note that these values are approximate and can vary depending on the specific type of structural steel, its composition, and the manufacturing process. Additionally, some properties may be affected by factors such as temperature, strain rate, and loading conditions.

Here are some common types of structural steel and their corresponding material properties:

A36 Steel: Yield Strength: 250 MPa (36,000 psi)

Ultimate Tensile Strength: 400 MPa (58,000 psi)

Elongation at Break: 20-30%

A572 Steel: Yield Strength: 290-345 MPa (42,000-50,000 psi)

Ultimate Tensile Strength: 450-550 MPa (65,000-80,000 psi)

Elongation at Break: 20-30%

A992 Steel: Yield Strength: 345-450 MPa (50,000-65,000 psi)

Ultimate Tensile Strength: 550-650 MPa (80,000-95,000 psi)

Elongation at Break: 20-30%

DEFINITION OF PROBLEM :

Geometry

- Hollow Cylinder:
 - Inner radius (r_i): 2.75 m.
 - Outer radius (r_o): 3 m.
 - Length (L): 10 m.
 - The cylinder is fixed at one end (no displacement or rotation allowed at that end).
-

Material Properties

- Material: Structural steel.
 - Elastic Properties:
 - Young's modulus (E): 200 GPa.
 - Poisson's ratio (ν): 0.3.
 - Creep Properties:
 - Norton's Power Law constants:
 - $A = 5 \times 10^{-10} \text{ MPa}^{-n} \text{ s}^{-1}$.
 - $n = 5$.
 - $Q = 200 \text{ kJ/mol}$.
 - Operating temperature (T): 300 K.
-

Loading Conditions

- Internal Pressure (P_i): 60 MPa (applied uniformly on the inner surface of the cylinder).
 - External Pressure (P_o): 0 MPa (assume atmospheric pressure or no external pressure).
 - Temperature: 300 K (constant throughout the analysis).
-

Boundary Conditions

- Fixed Support: One end of the cylinder is fixed (no displacement or rotation allowed).
 - Free End: The other end is free to deform.
-

Analysis Type

- Static Structural Analysis with Creep Effects:
 - The analysis will consider time-dependent creep deformation under constant stress and temperature.
 - The total analysis time is 1 year ($3.15 \times 10^7 \text{ s}$).

- **Summary of Inputs**

Parameter	Value
Inner radius (r_i)	2.75 m
Outer radius (r_o)	3 m
Length (L)	10 m
Internal pressure (P_i)	60 MPa
External pressure (P_o)	0 MPa
Temperature (T)	300 K
Young's modulus (E)	200 GPa
Poisson's ratio (ν)	0.3
Creep constants (A)	$5 \times 10^{-10} \text{ MPa}^{-n} \text{ s}^{-1}$
Stress exponent (n)	5
Activation energy (Q)	200 kJ/mol
Yield strength (σ_y)	250 MPa

METHODOLOGY:

Geometry Creation

- **Open ANSYS Workbench:**
- Start a new project and select the "Static Structural" template.

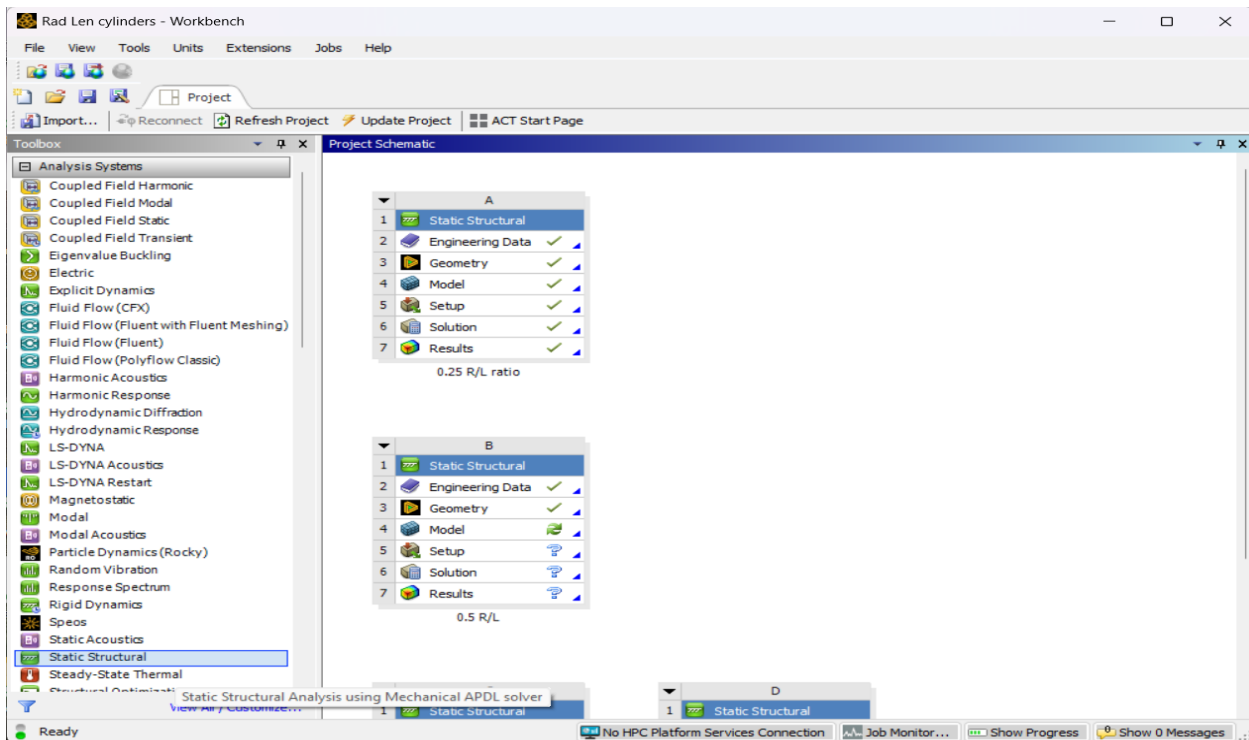


Fig 4.1 Static Structural

4.2 Define material properties :

In engineering data apply all related properties regarding specification of structural steel.

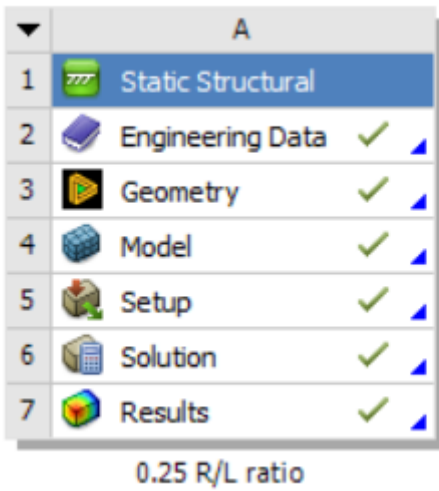


Fig 4.2 List of Static Structural

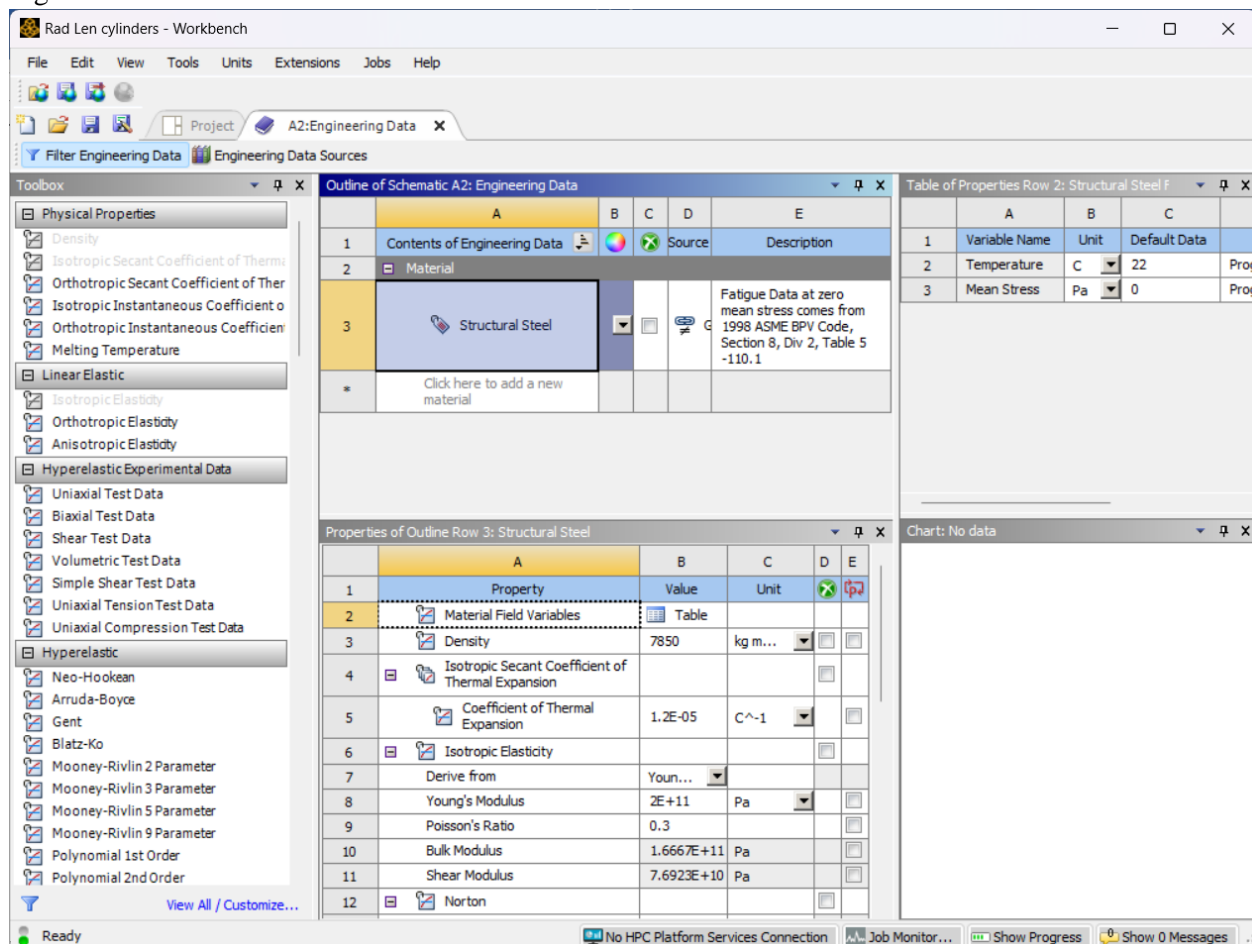


Fig 4.3 Material properties

Norton			
Reference Units (Length, Time, Temperature, Force)	m, s,...		
Creep Constant 1	1E-06		
Creep Constant 2	5		
Creep Constant 3	24.1		
Strain-Life Parameters			
Display Curve Type	Strai...		
Strength Coefficient	9.2E+08	Pa	
Strength Exponent	-0.106		
Ductility Coefficient	0.213		

Fig 4.4 Creep properties

4.3 GEOMETRY:

Based on required geometry the cylinder is formed through design modeler

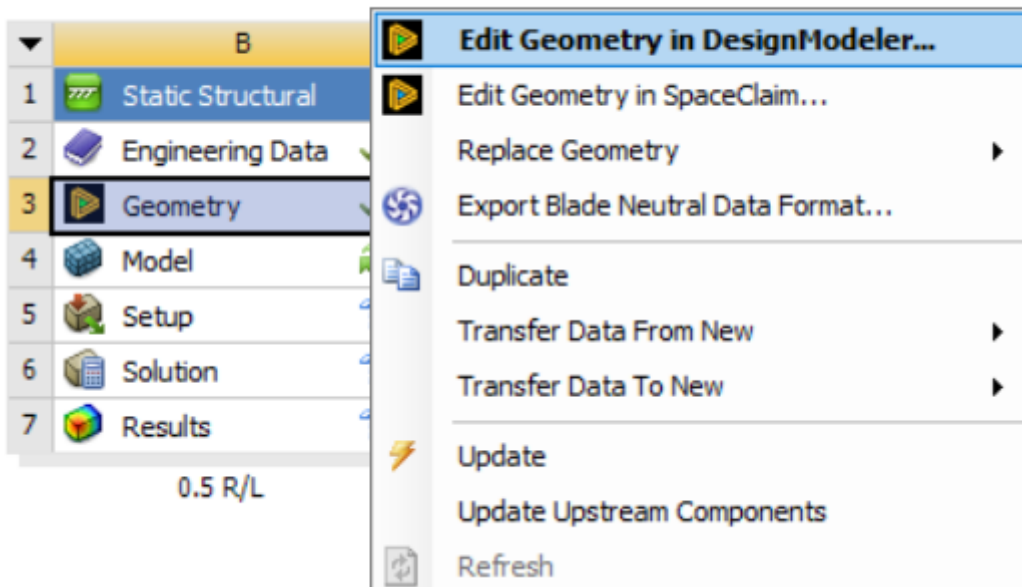


Fig 4.5 Design modeler

The cylinder is designed based on specified ratio of Radius and length

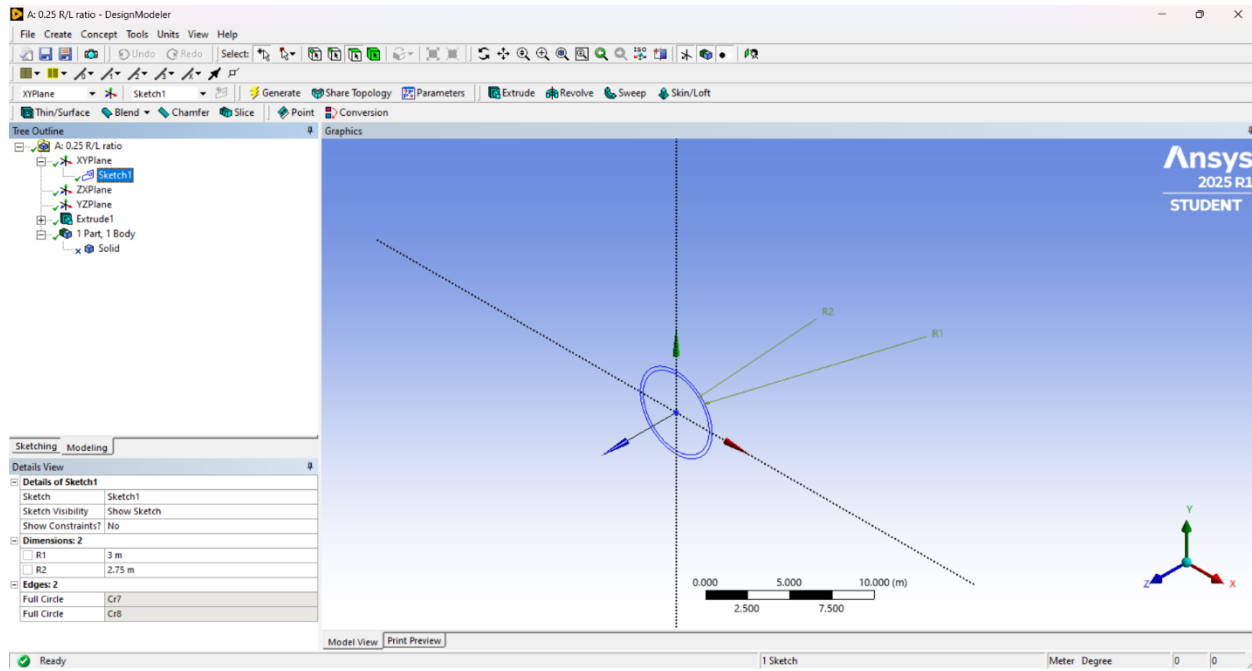


Fig 4.6 2D Sktech

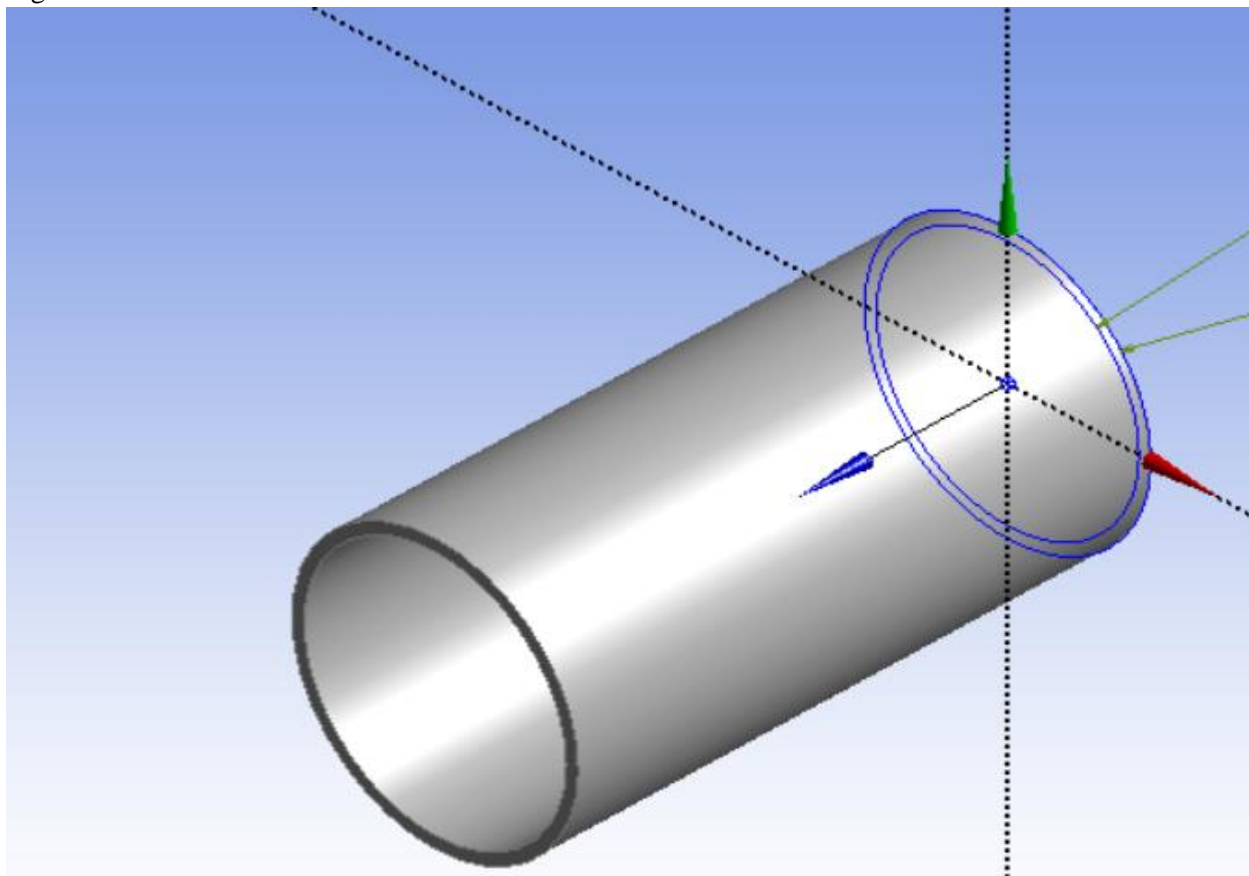


Fig 4.7 ISOMETRIC VIEW

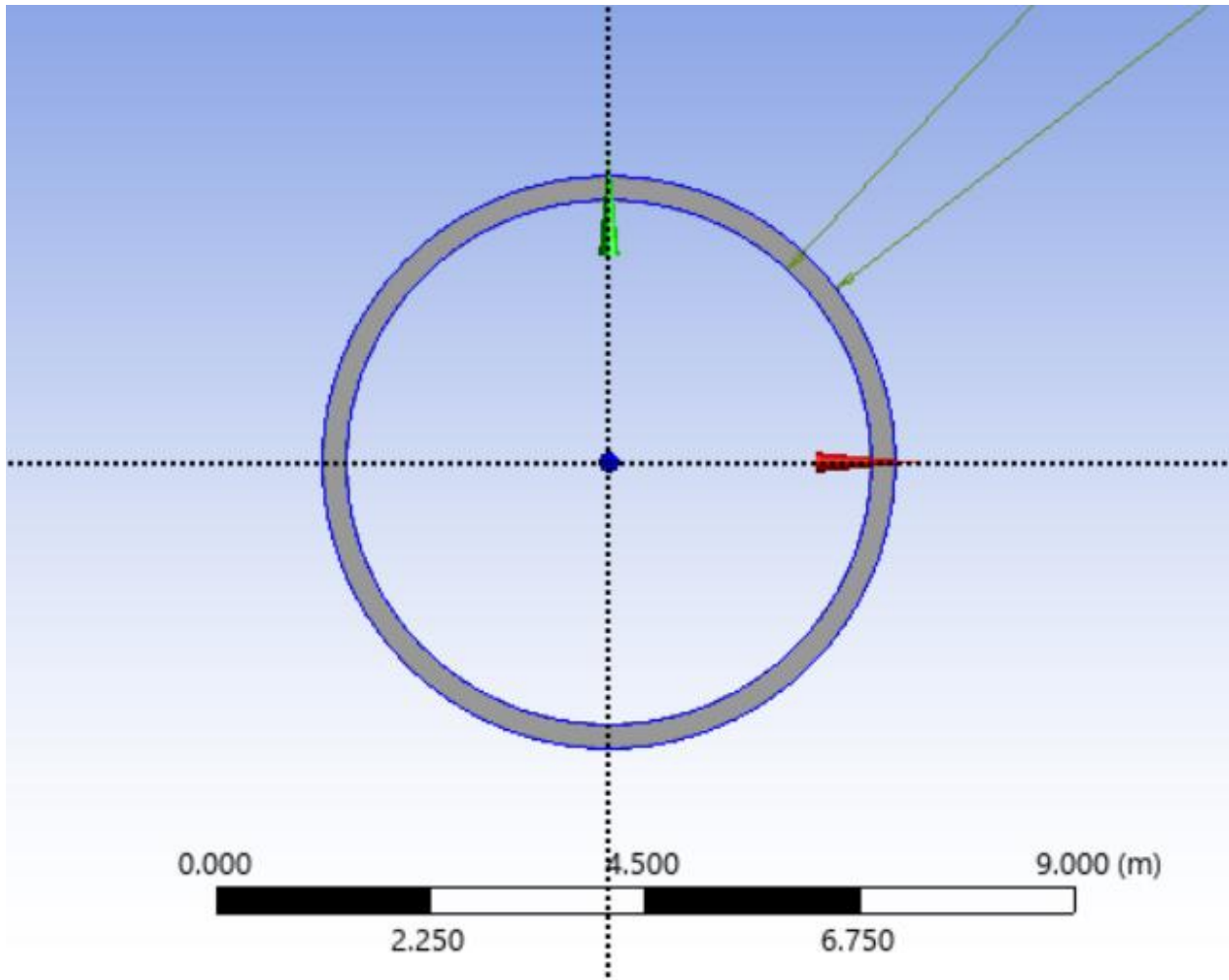


Fig 4.8 FRONT VIEW

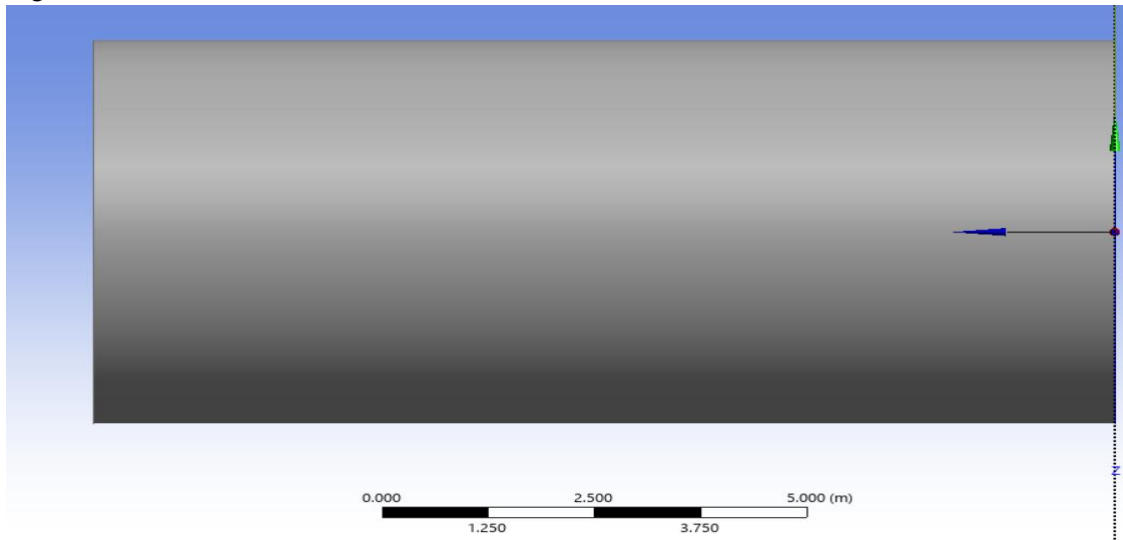


Fig 4.9 SIDE VIEW



Fig 4.10 TOP VIEW

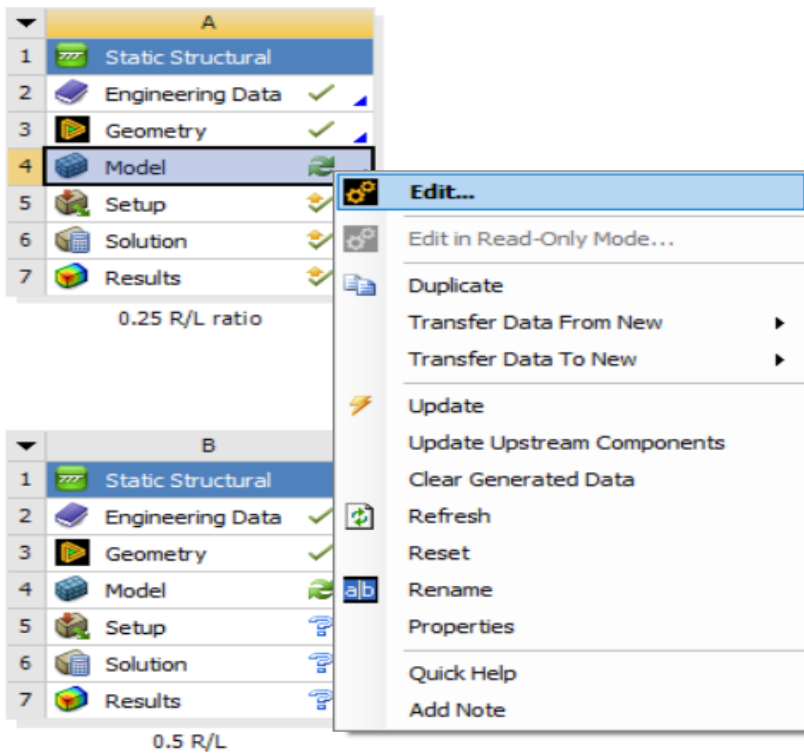


Fig 4.11 Model Analysis

Chapter – 5 RESULT AND GRAPHS

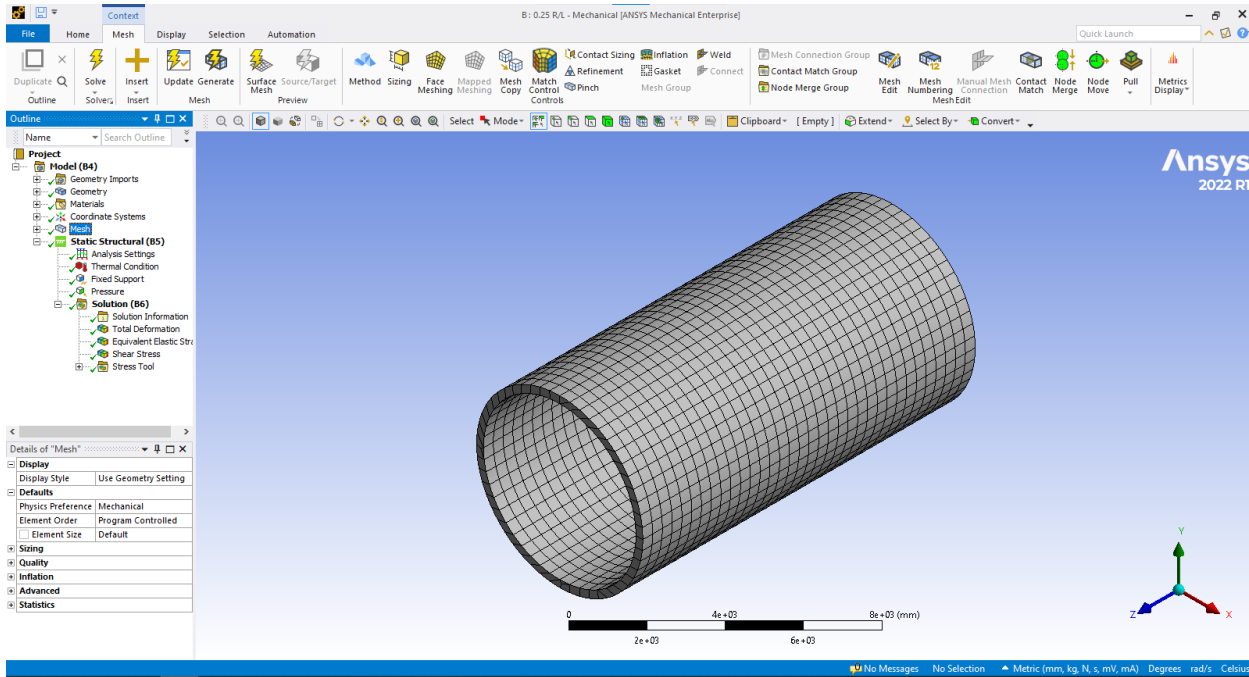


Fig 5.1 Meshing

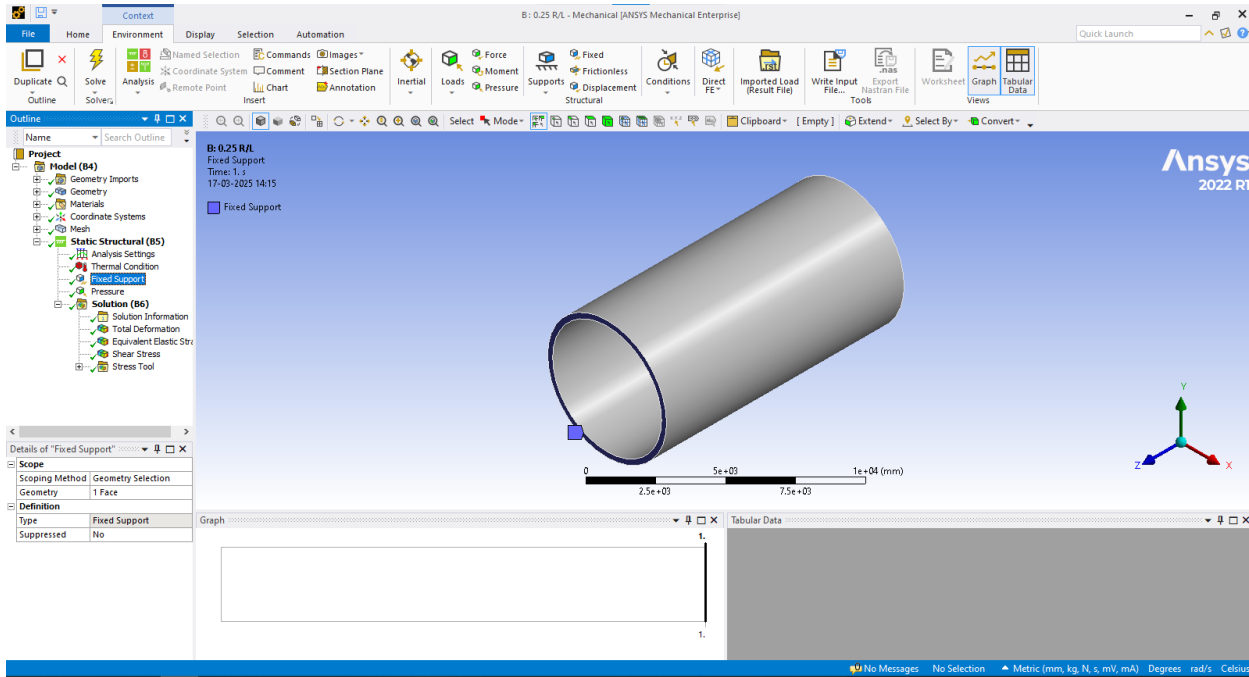


Fig 5.2 Fixed Support

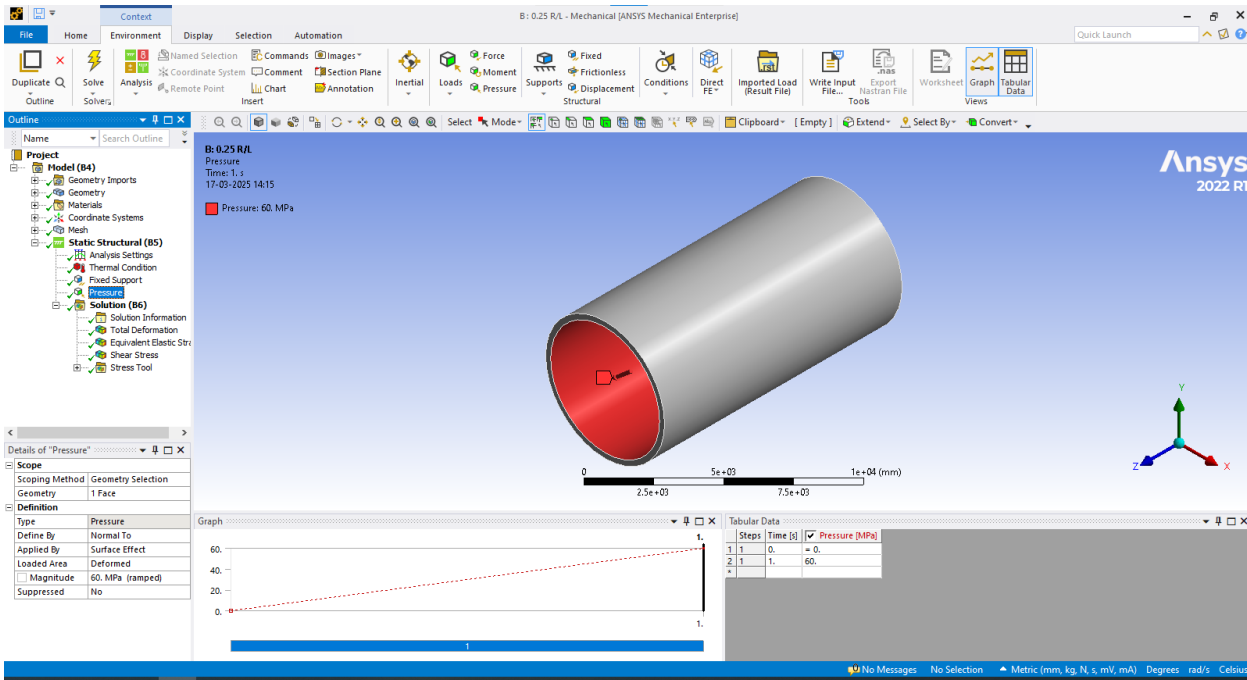


Fig 5.3 Internal Pressure

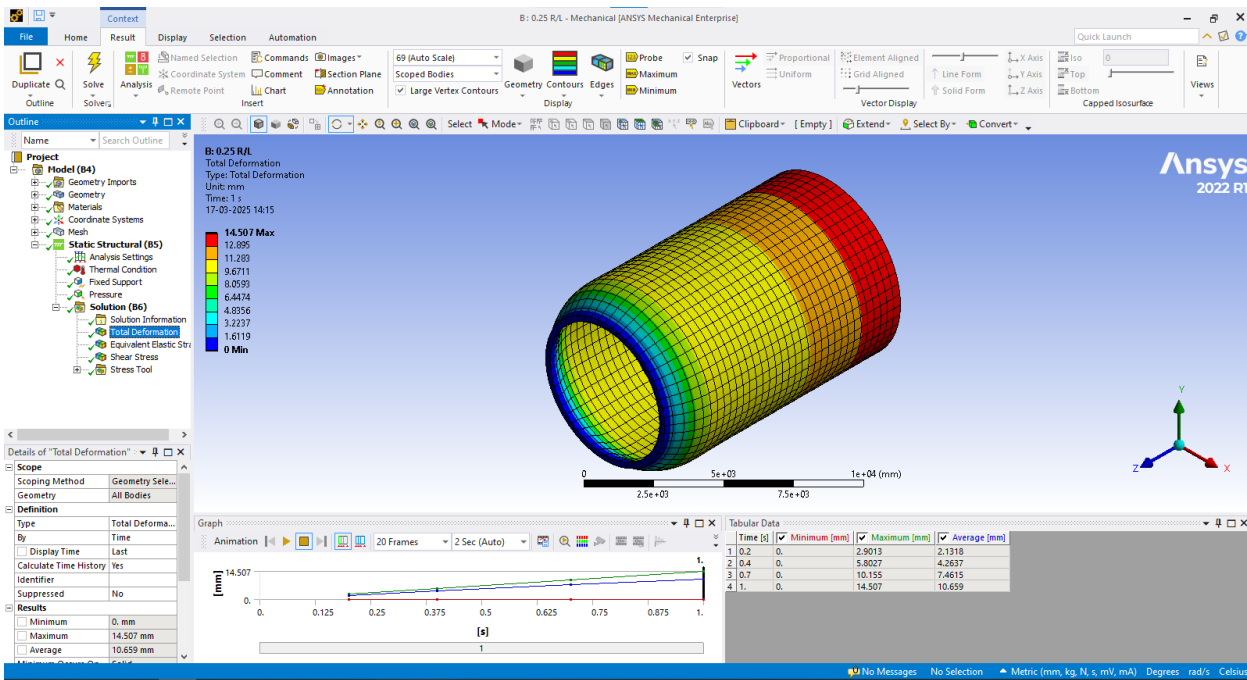


Fig 5.4 Total Deformation

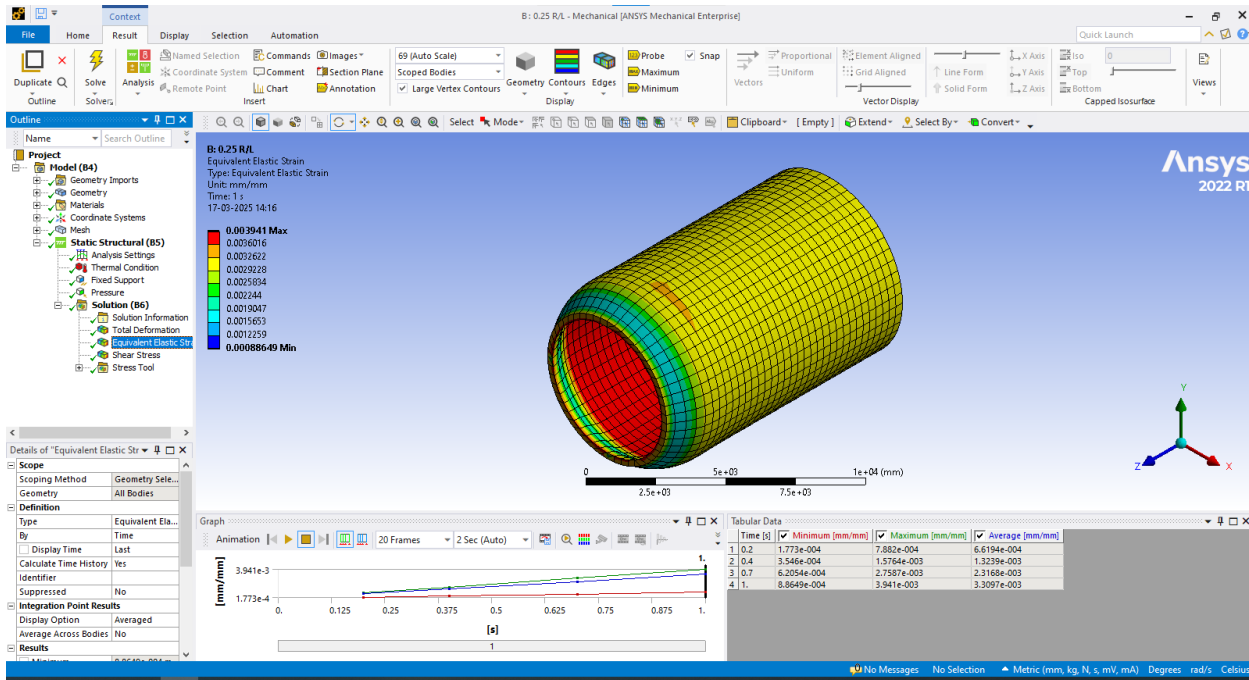


Fig 5.5 Equivalent Elastic Strain

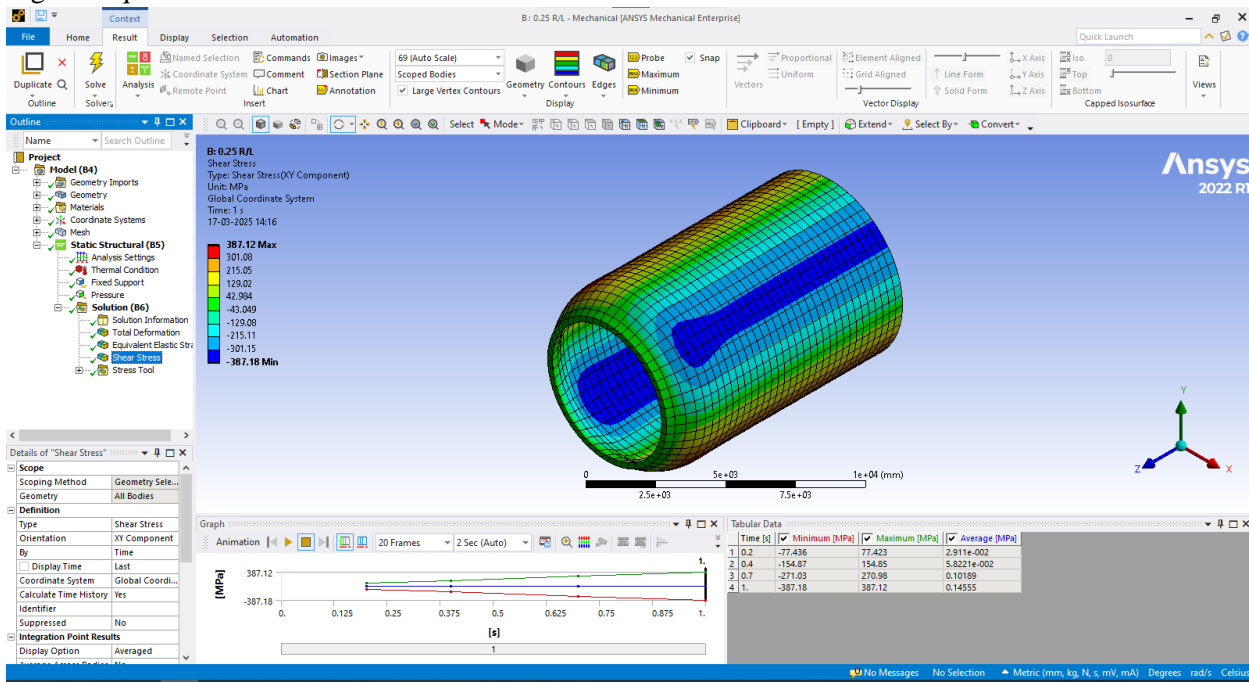


Fig 5.6 Shear Stress

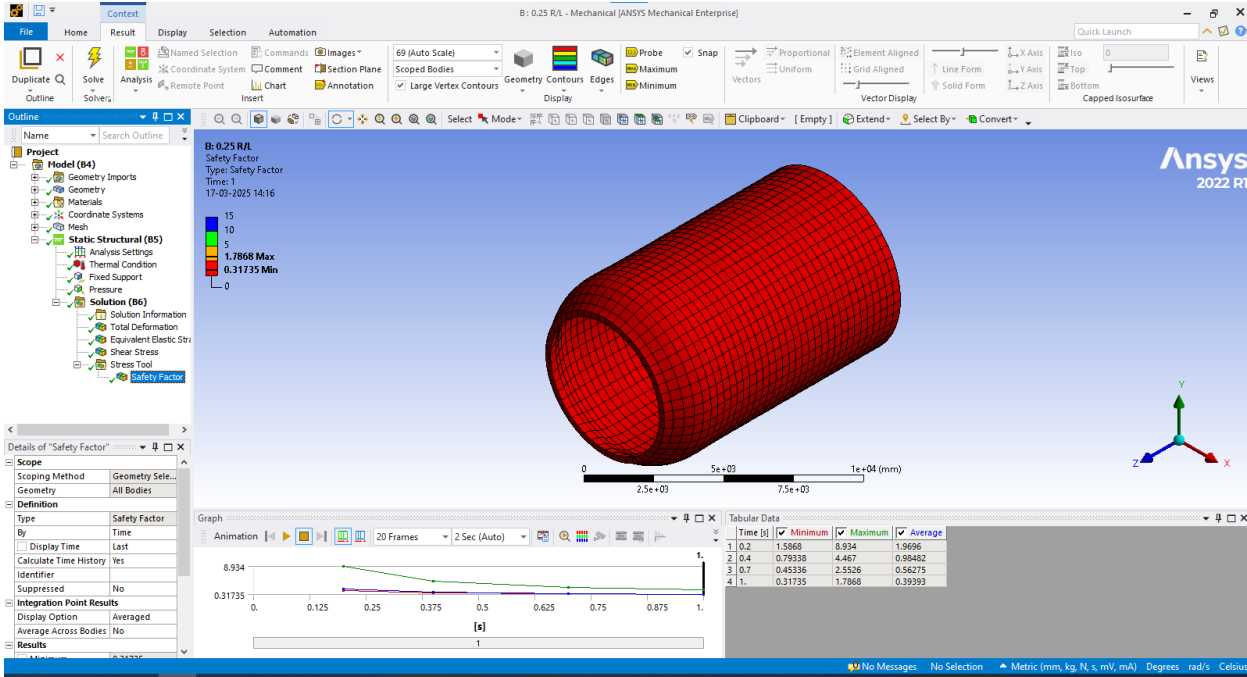


Fig 5.7 Safety Factor

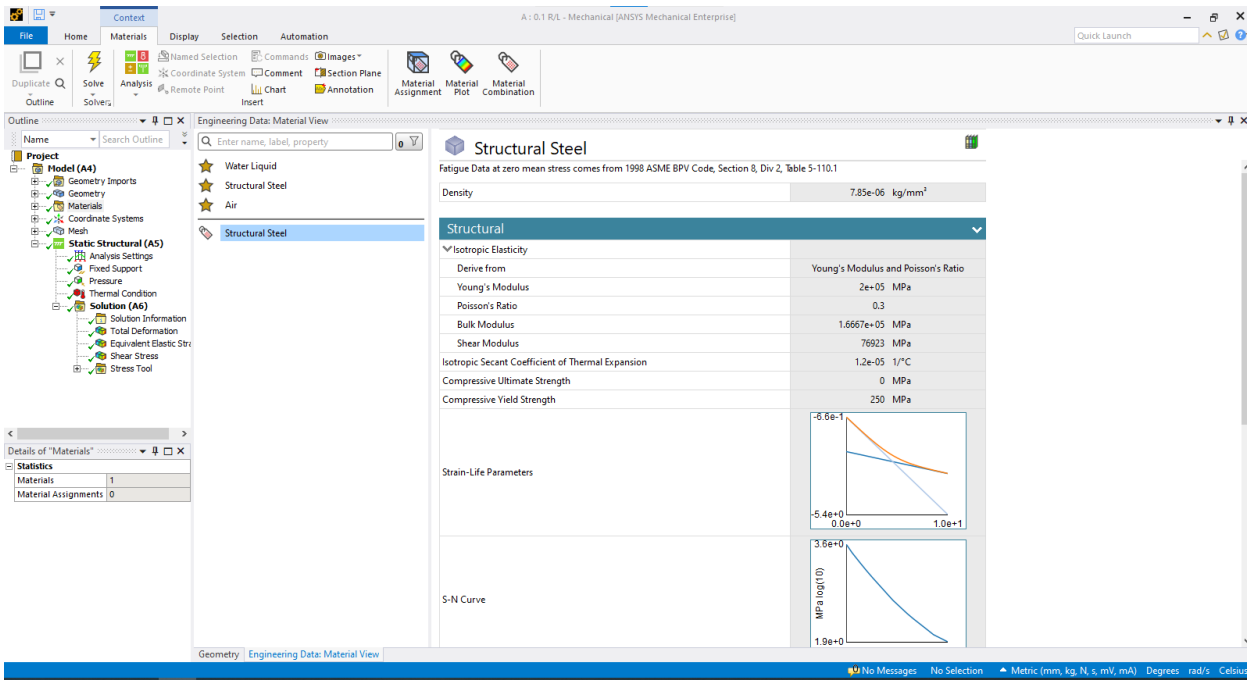


Fig 5.8 Material properties

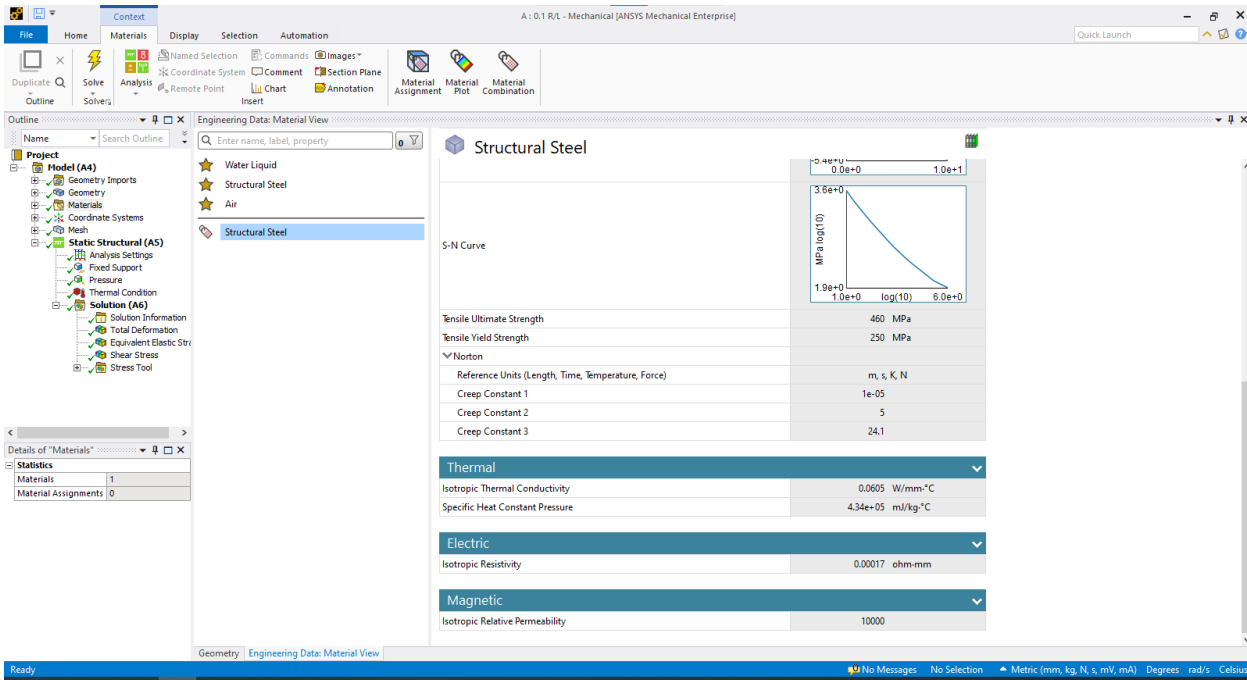


Fig 5.9 Material Properties

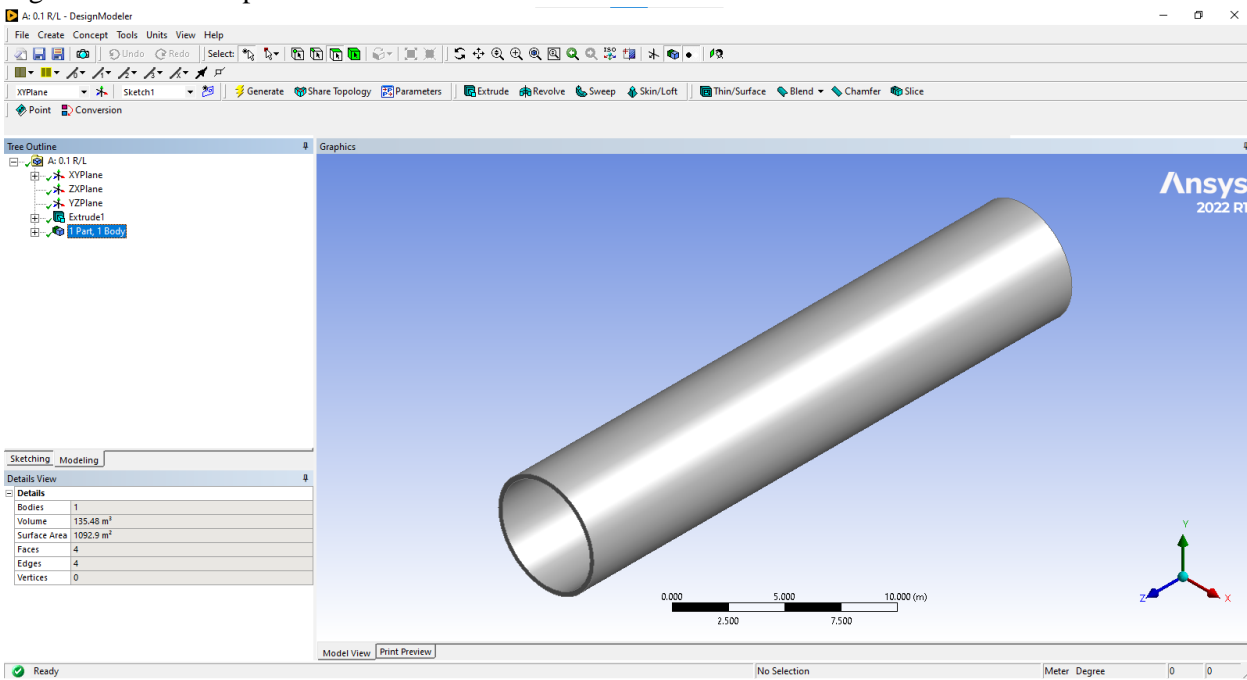


Fig 5.10 ISOMETRIC VIEW

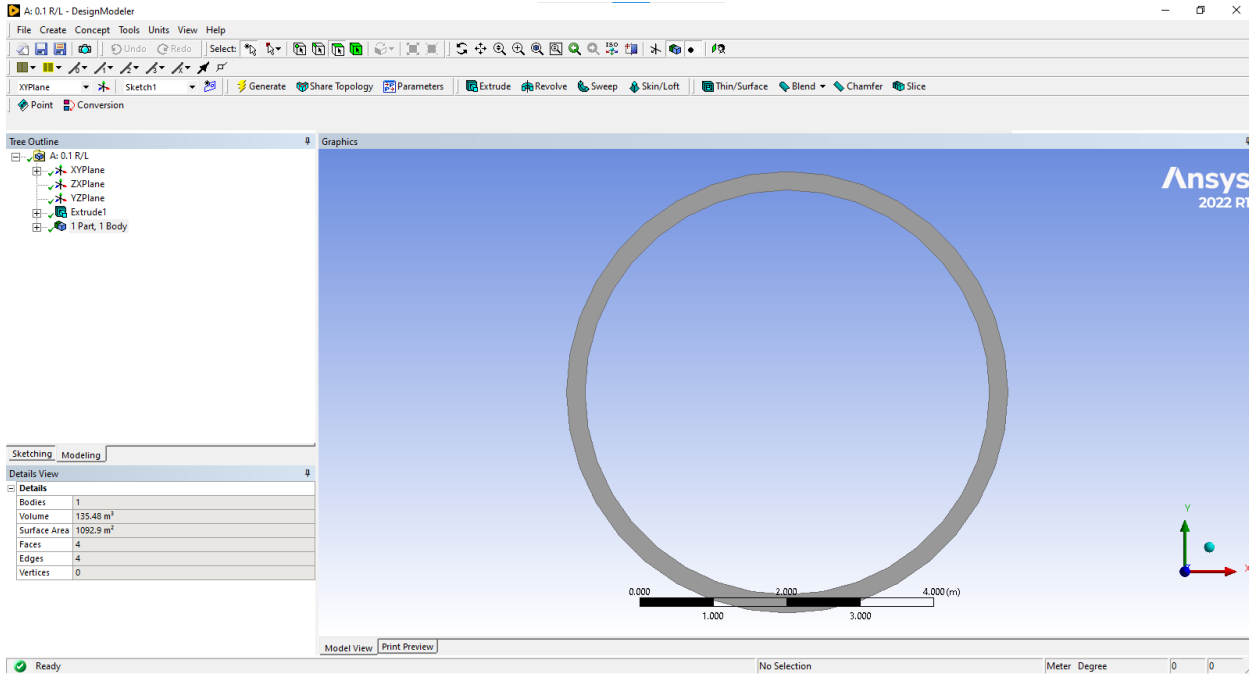


Fig 5.11 Front View

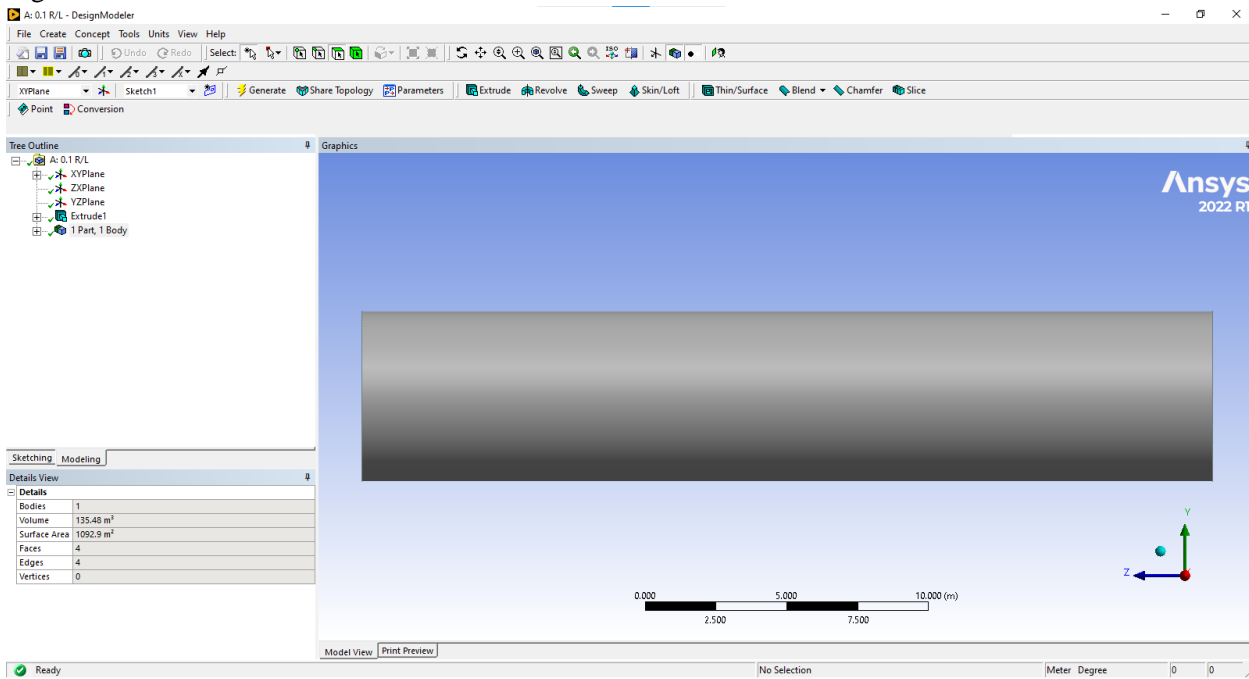


Fig 5.12 Side View/ Top View

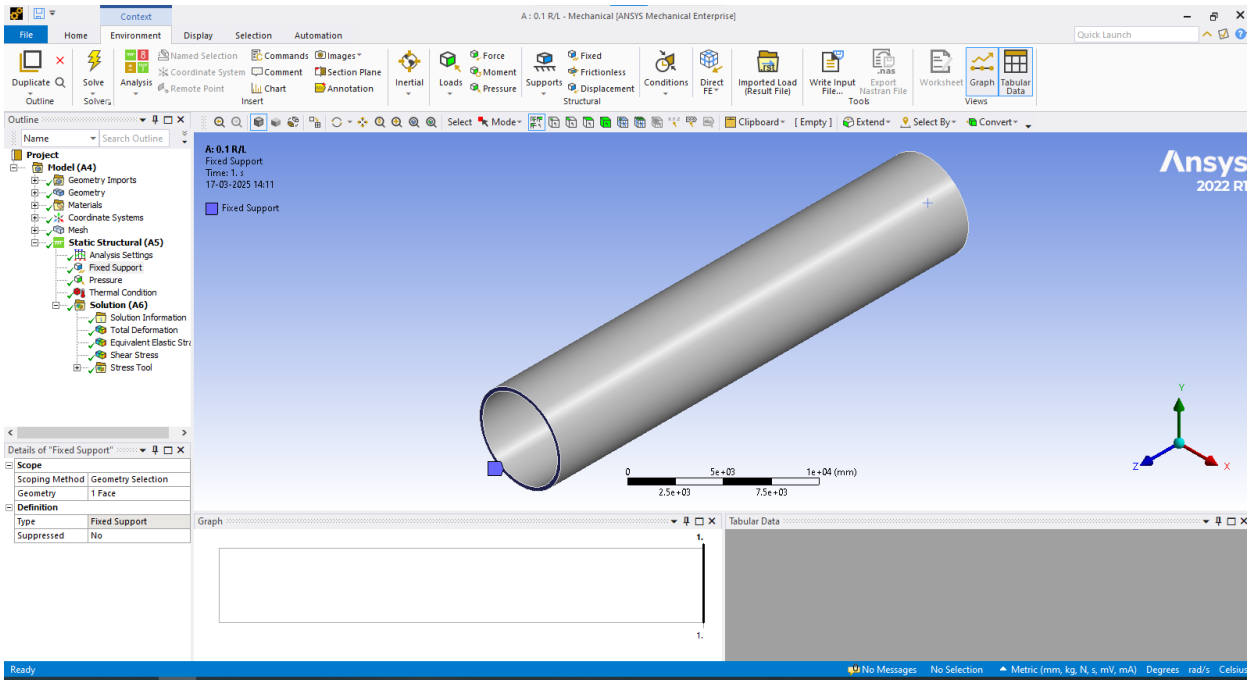


Fig 5.13 Fixed Support

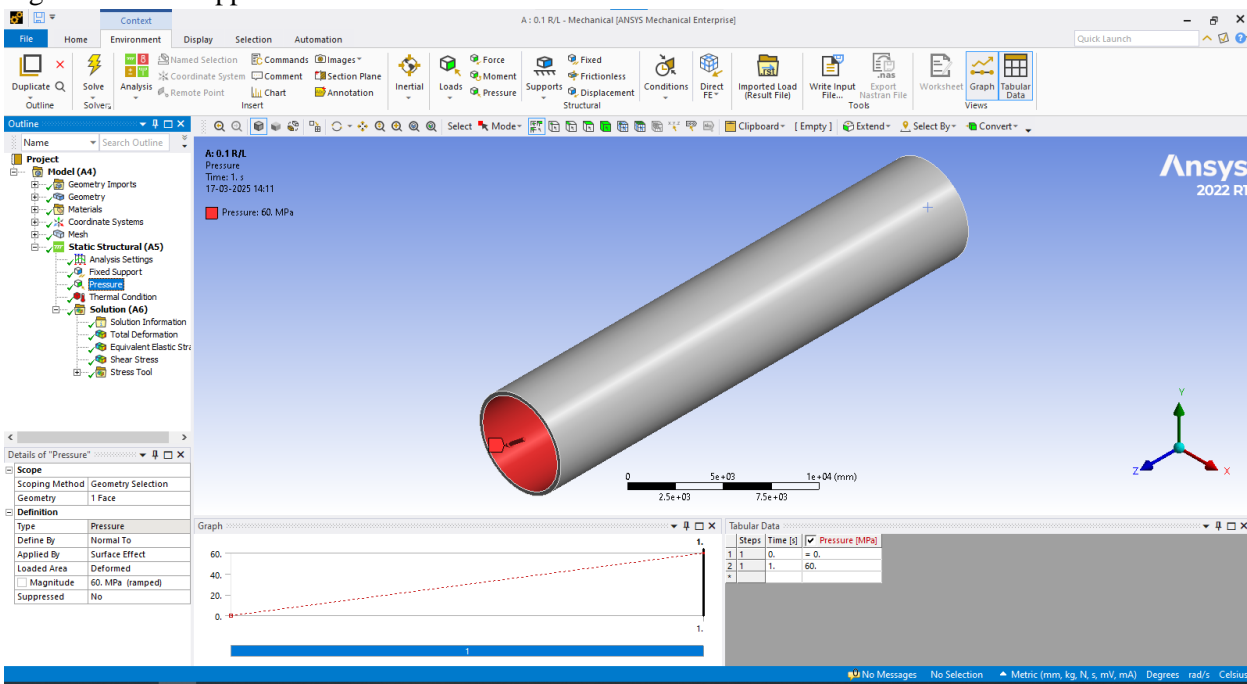


Fig 5.14 Internal Pressure

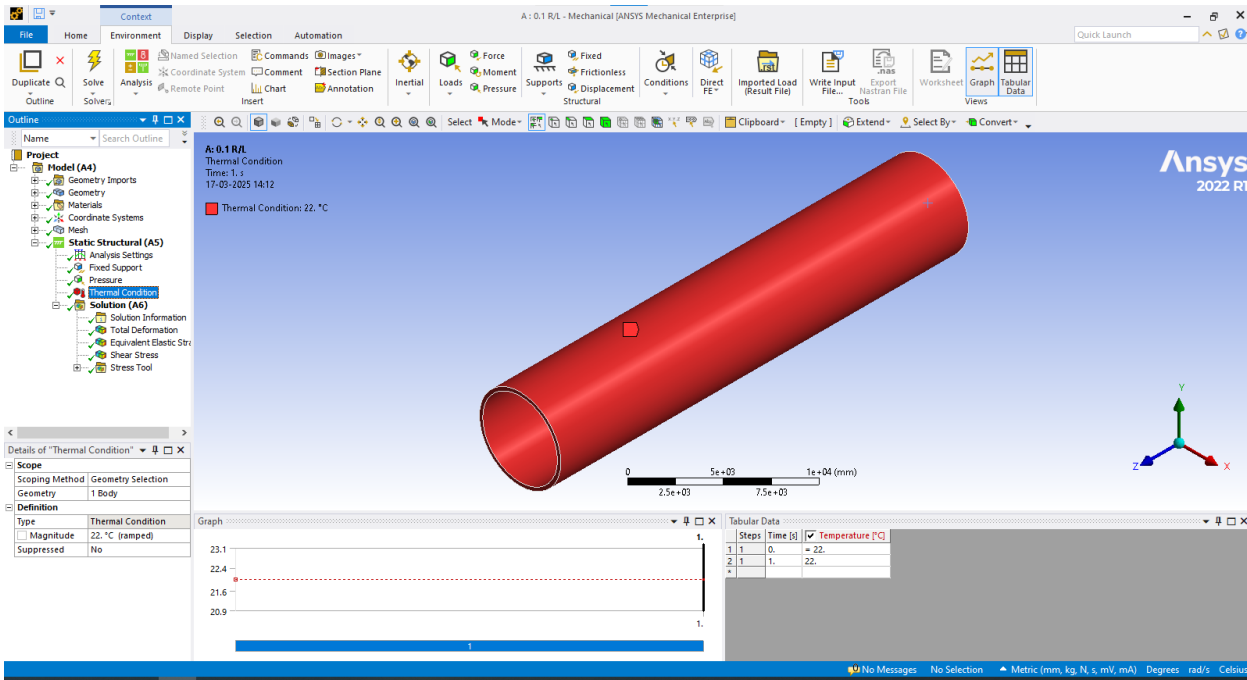


Fig 5.15 Thermal Condition

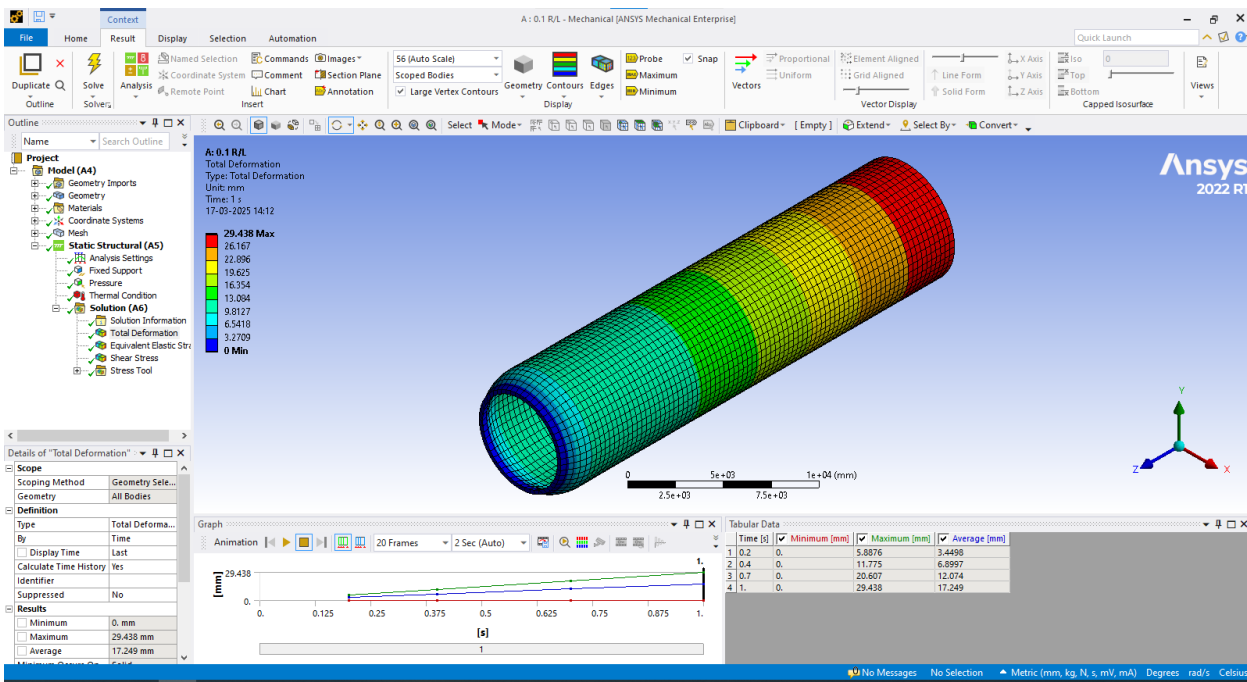


Fig 5.16 Total Deformation

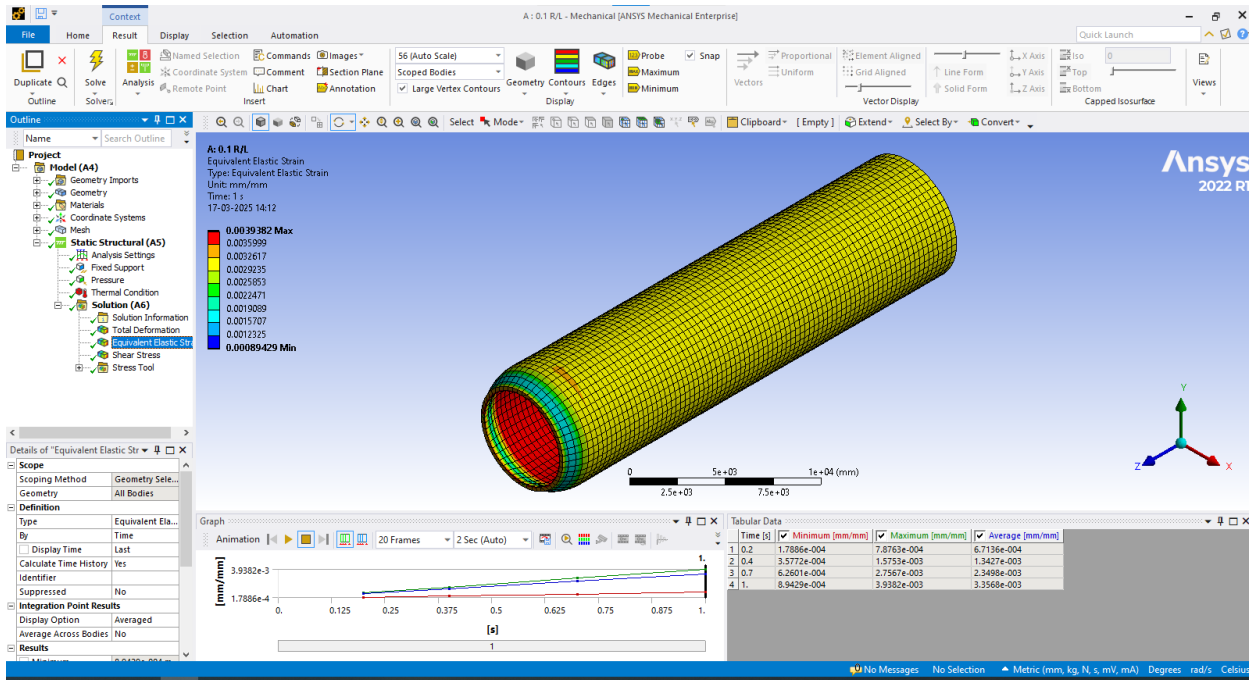


Fig 5.17 Equivalent Elastic Strain

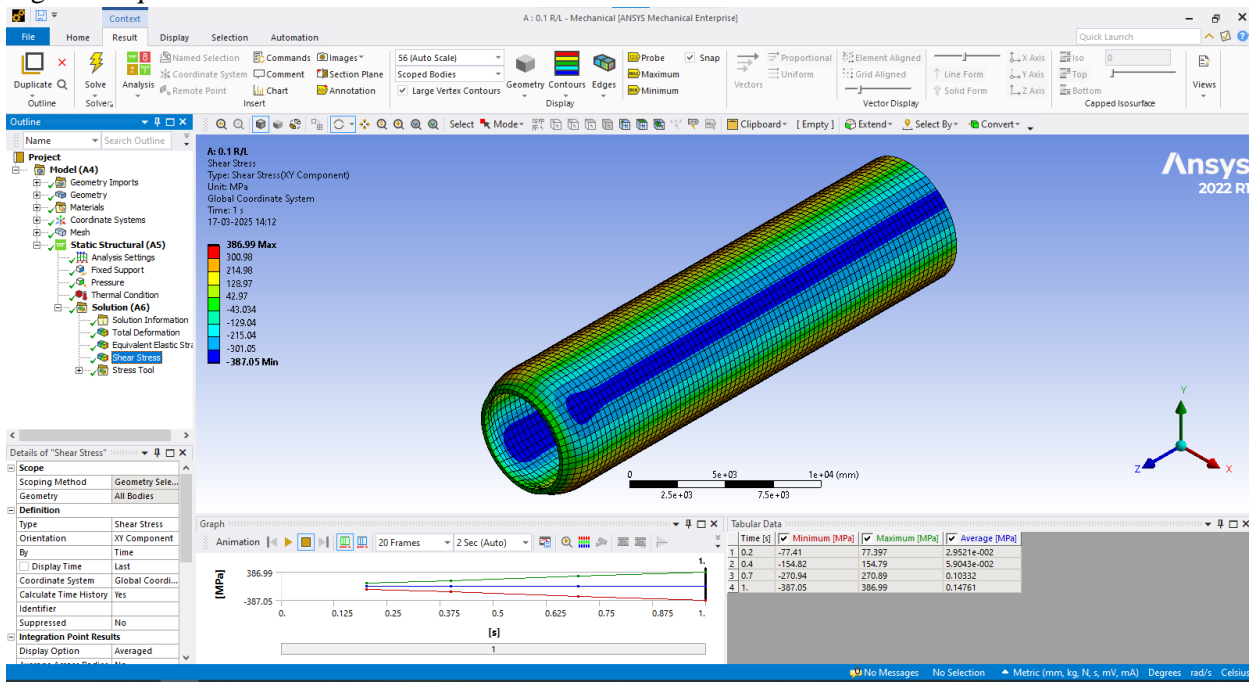


Fig 5.18 Shear Stress

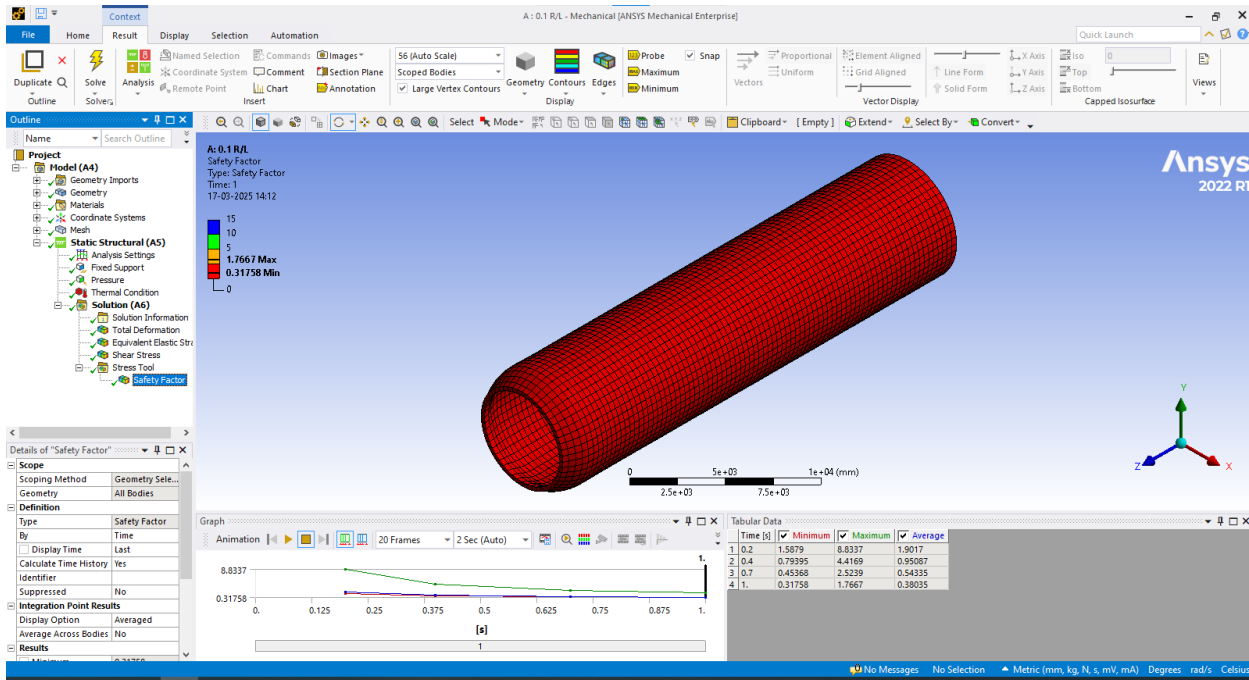


Fig 5.19 Safety Factor

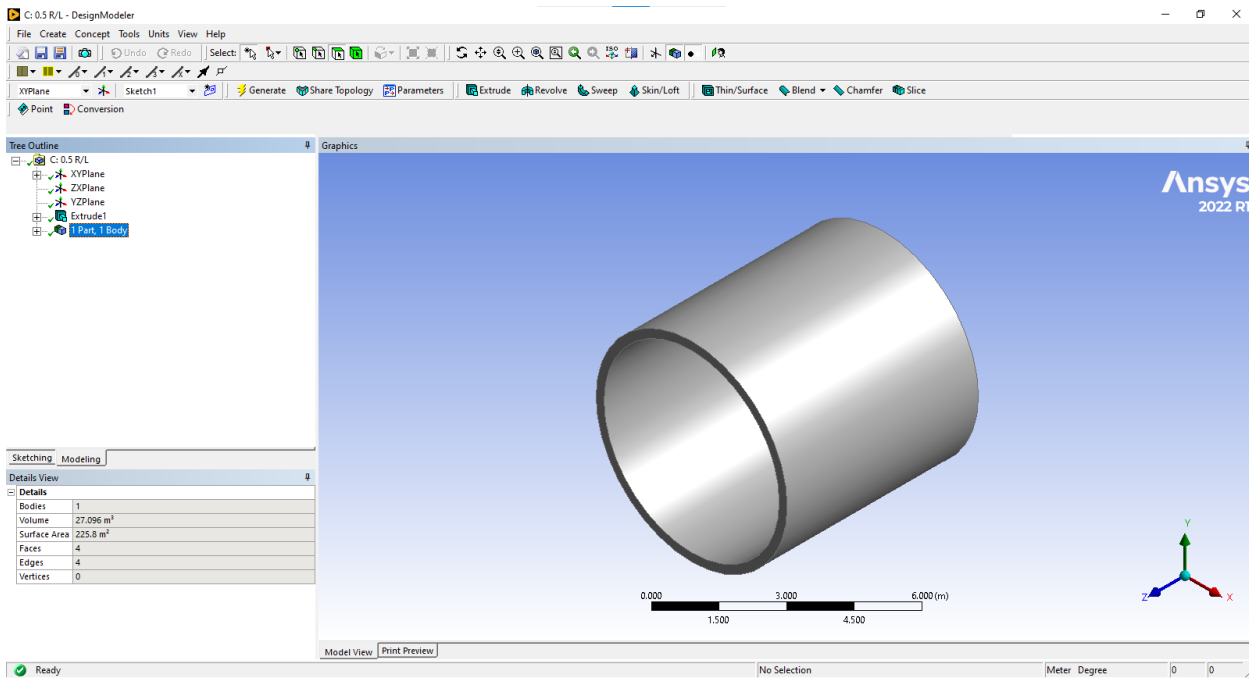


Fig 5.20 ISOMETRIC VIEW

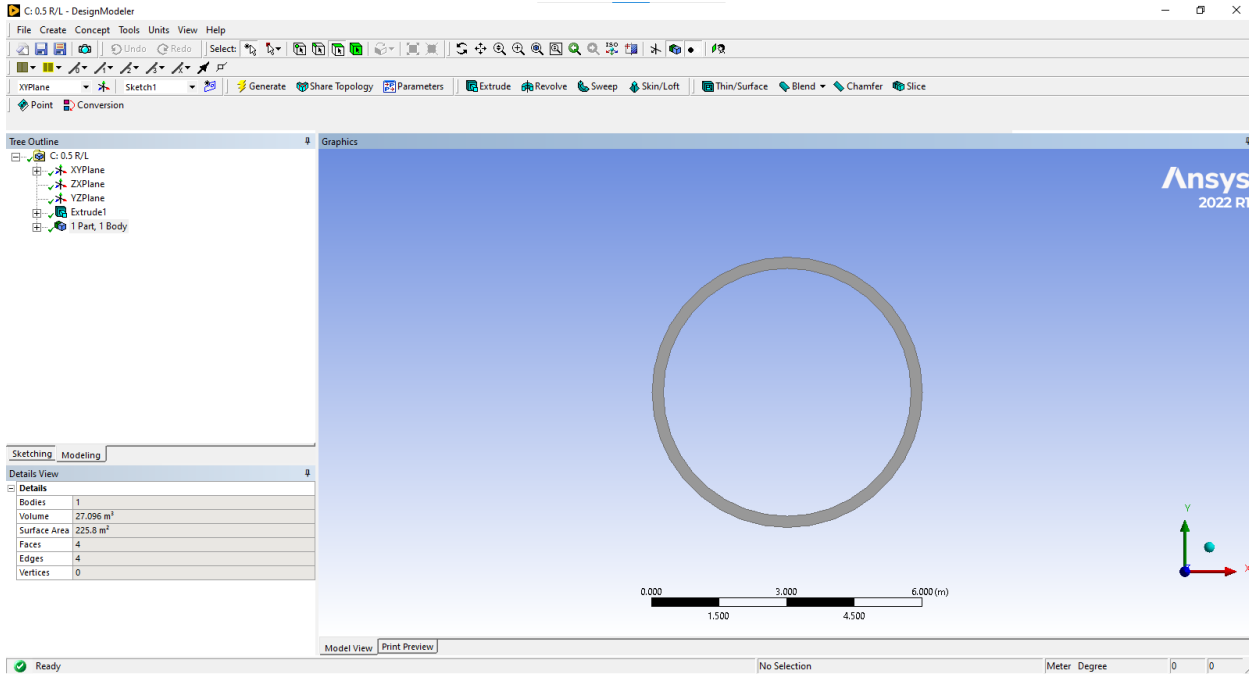


Fig 5.21 Front View

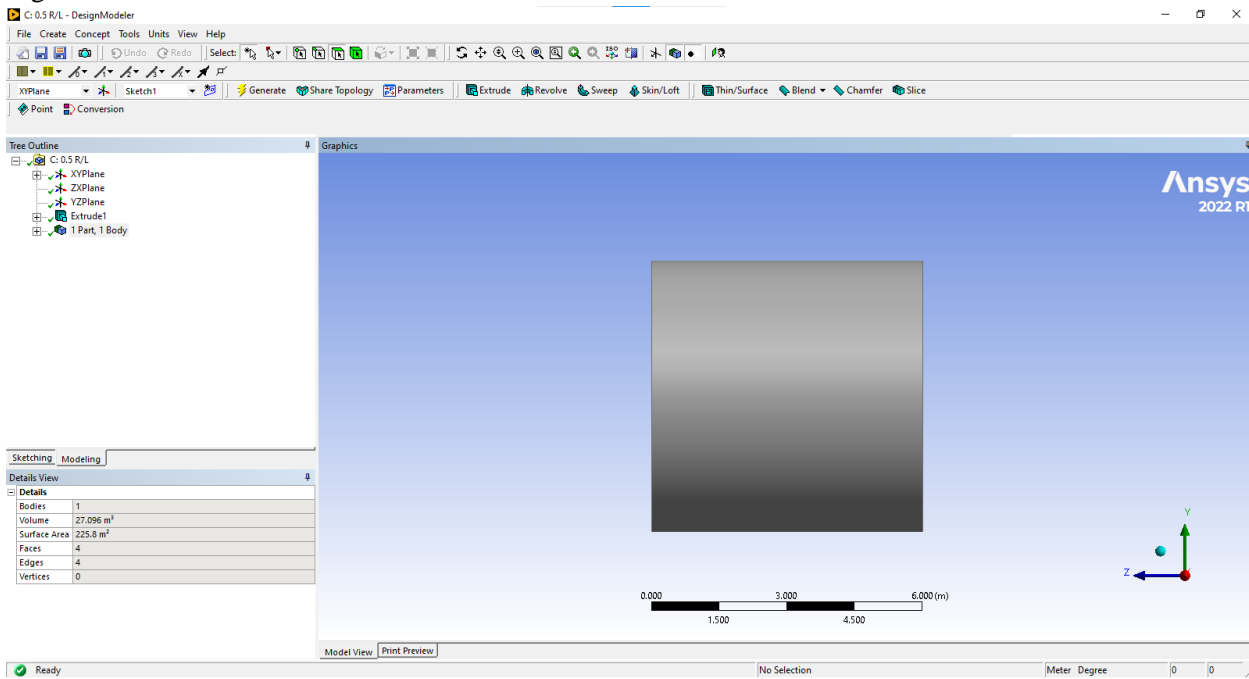


Fig 5.22 Side View

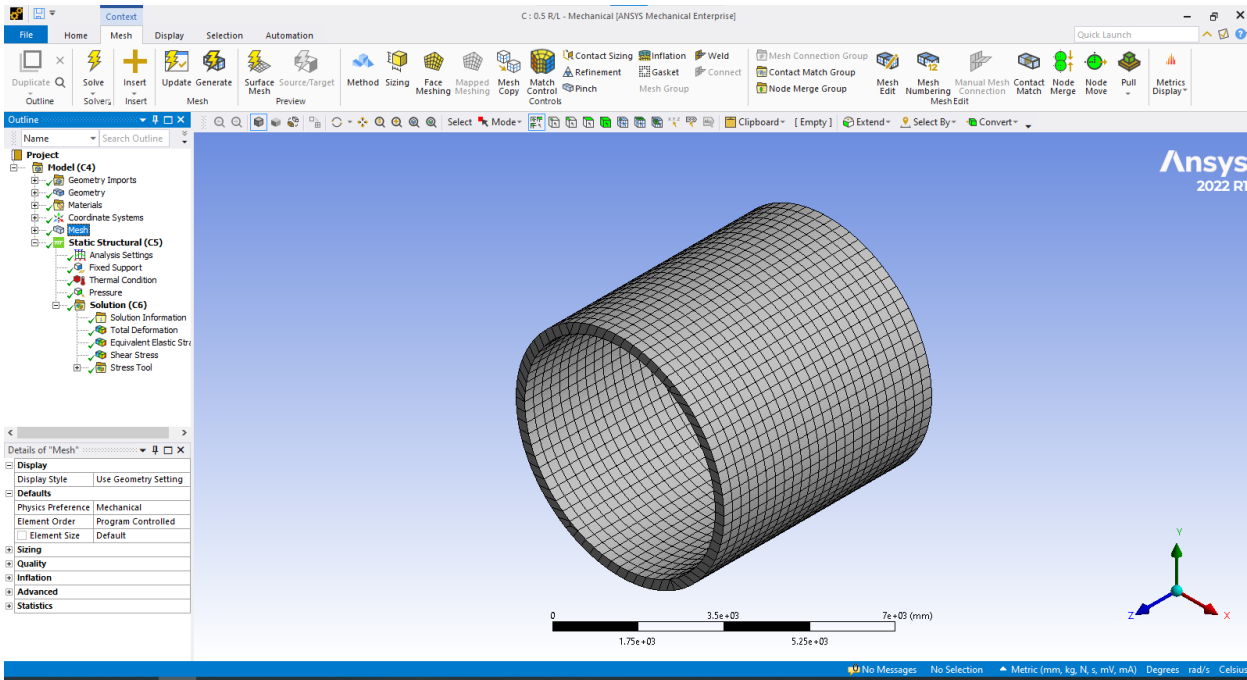


Fig 5.23 Meshing

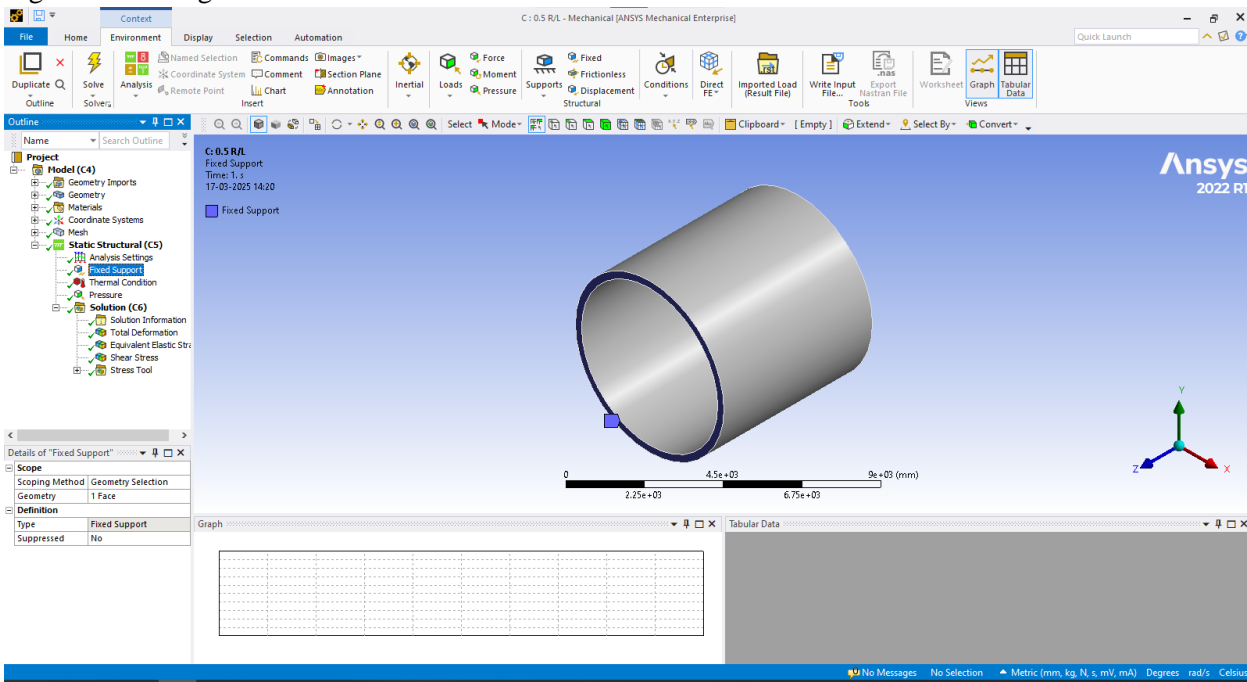


Fig 5.24 Fixed Support

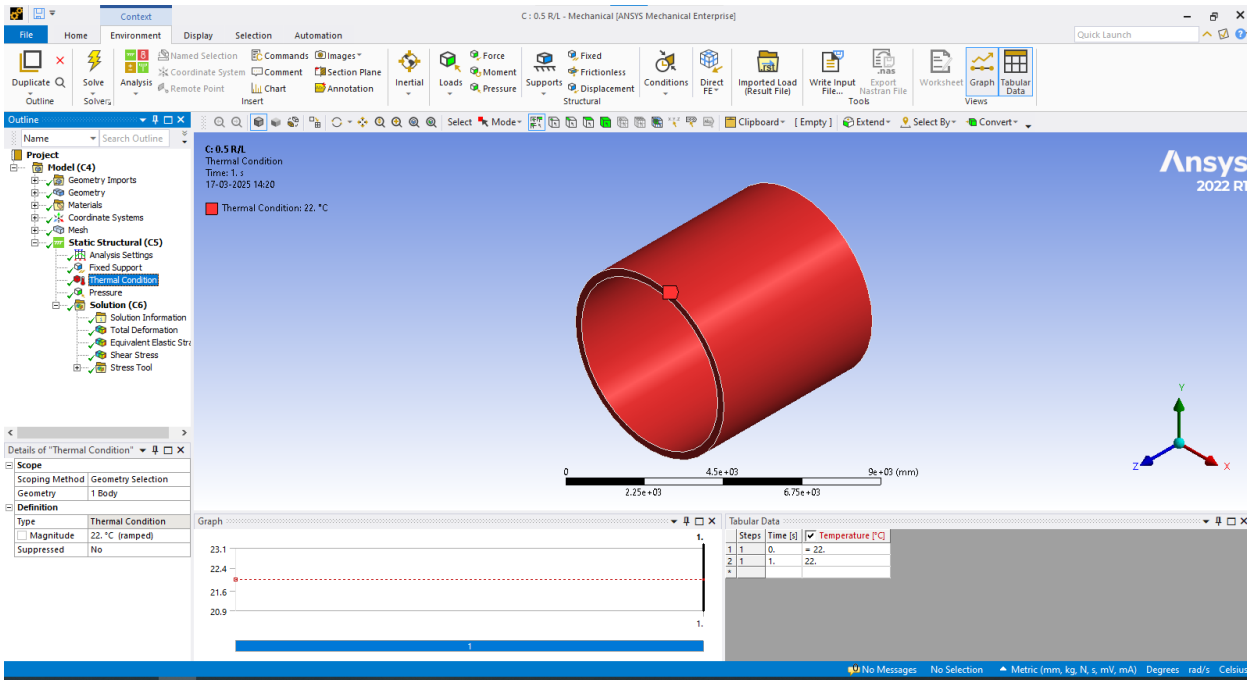


Fig 5.25 Thermal Condition

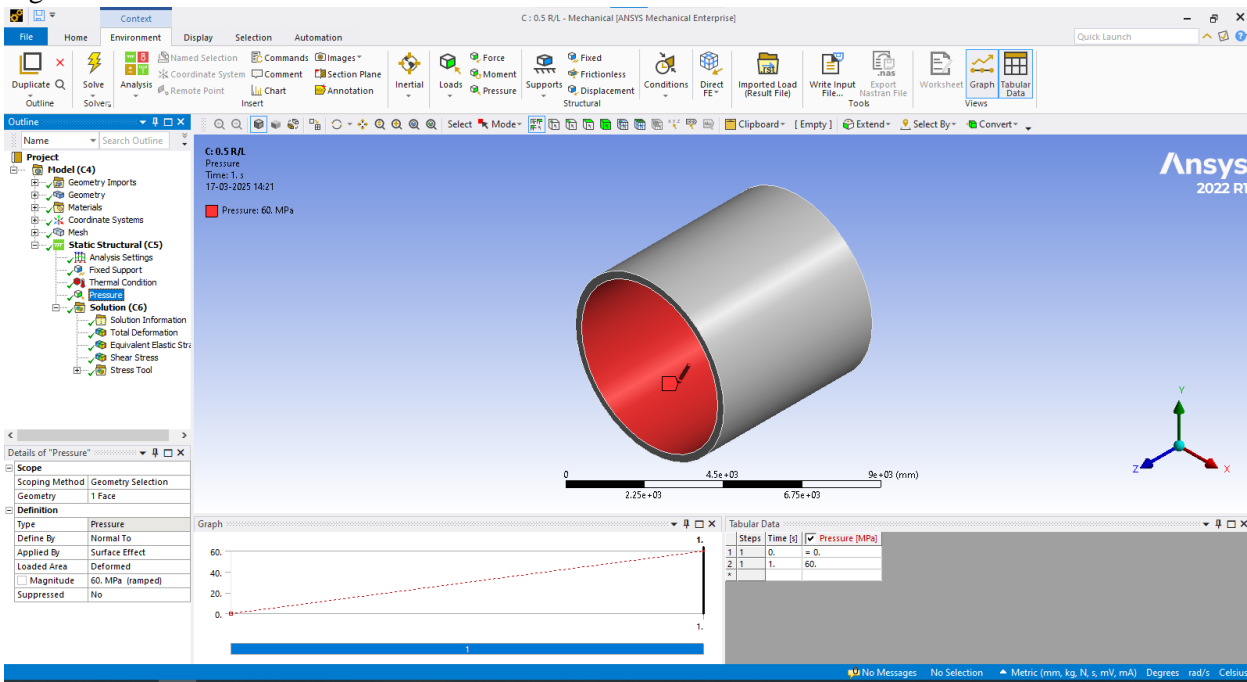


Fig 5.26 Internal Pressure

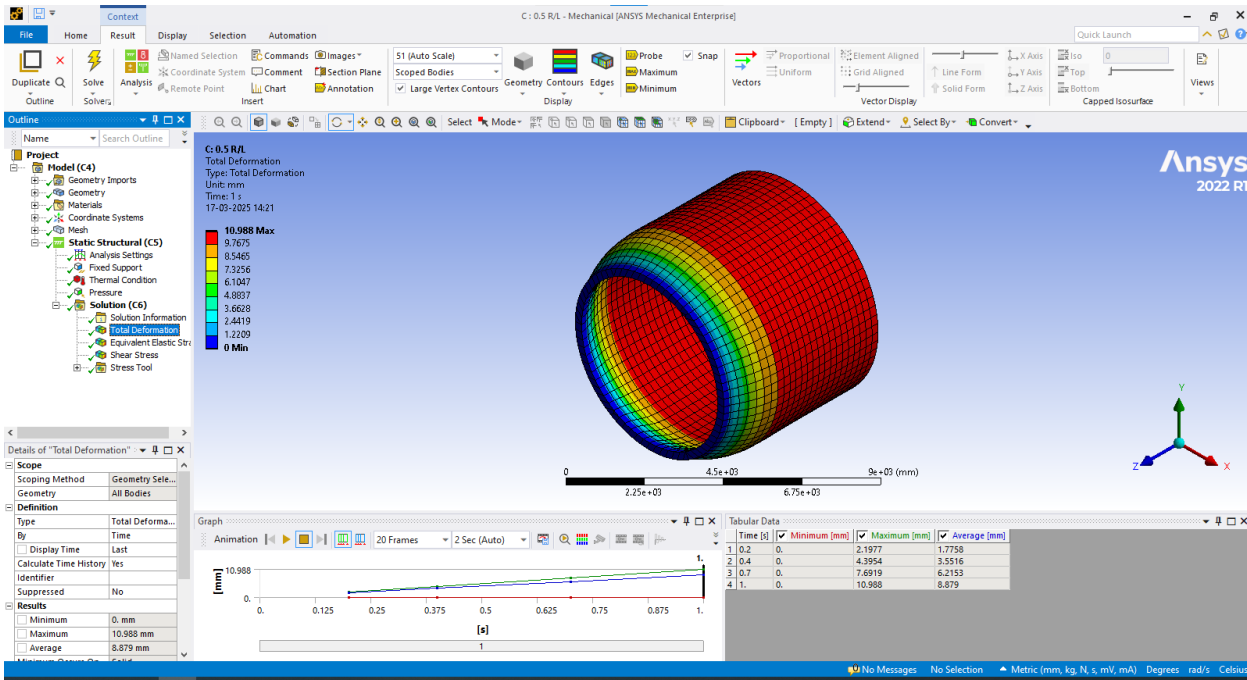


Fig 5.27 Total Deformation

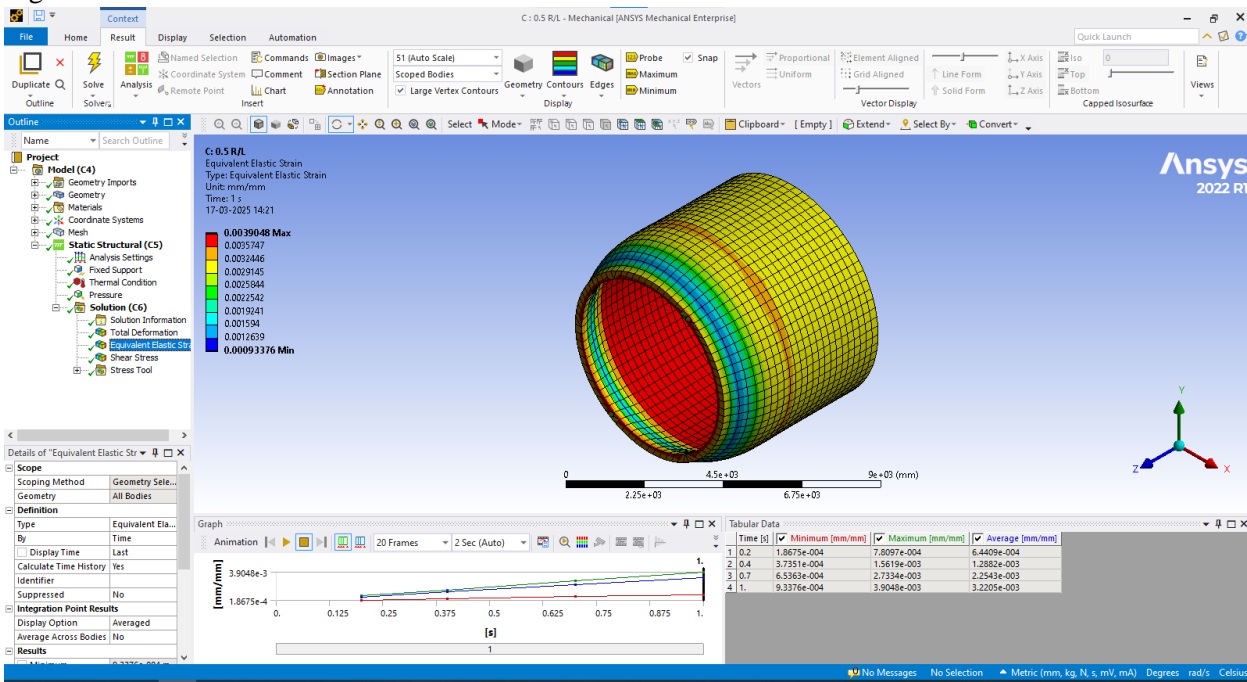


Fig 5.28 Equivalent Elastic Strain

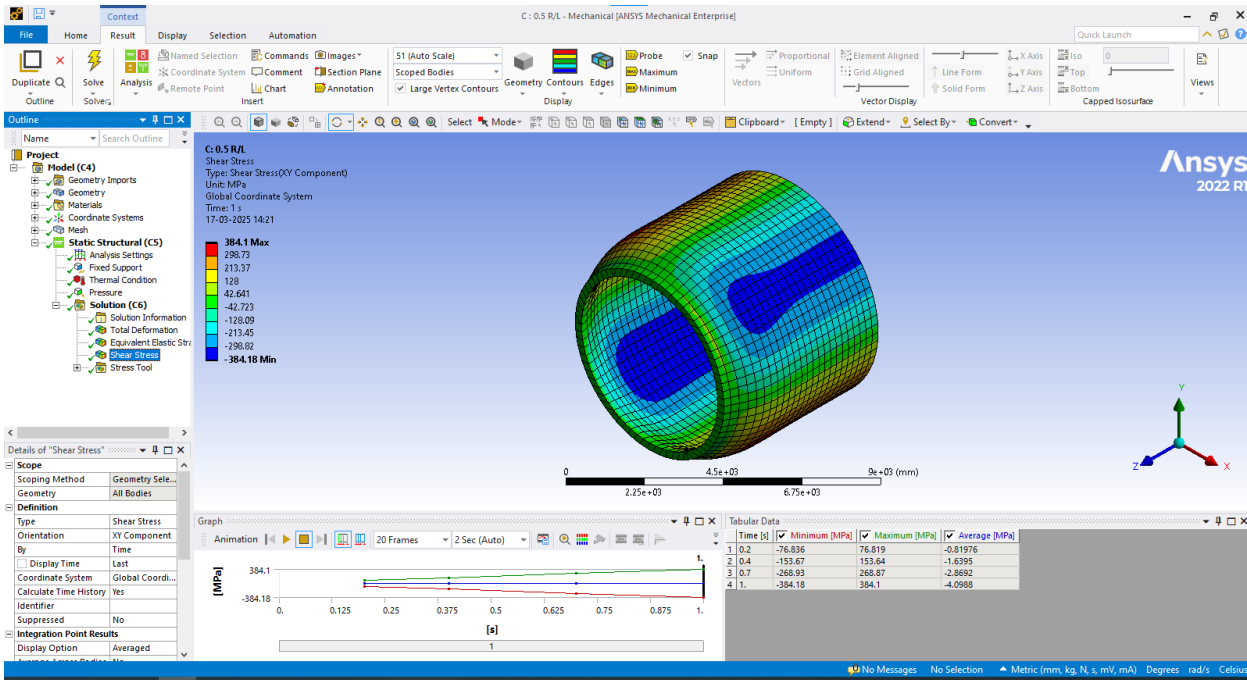


Fig 5.29 Shear Stress

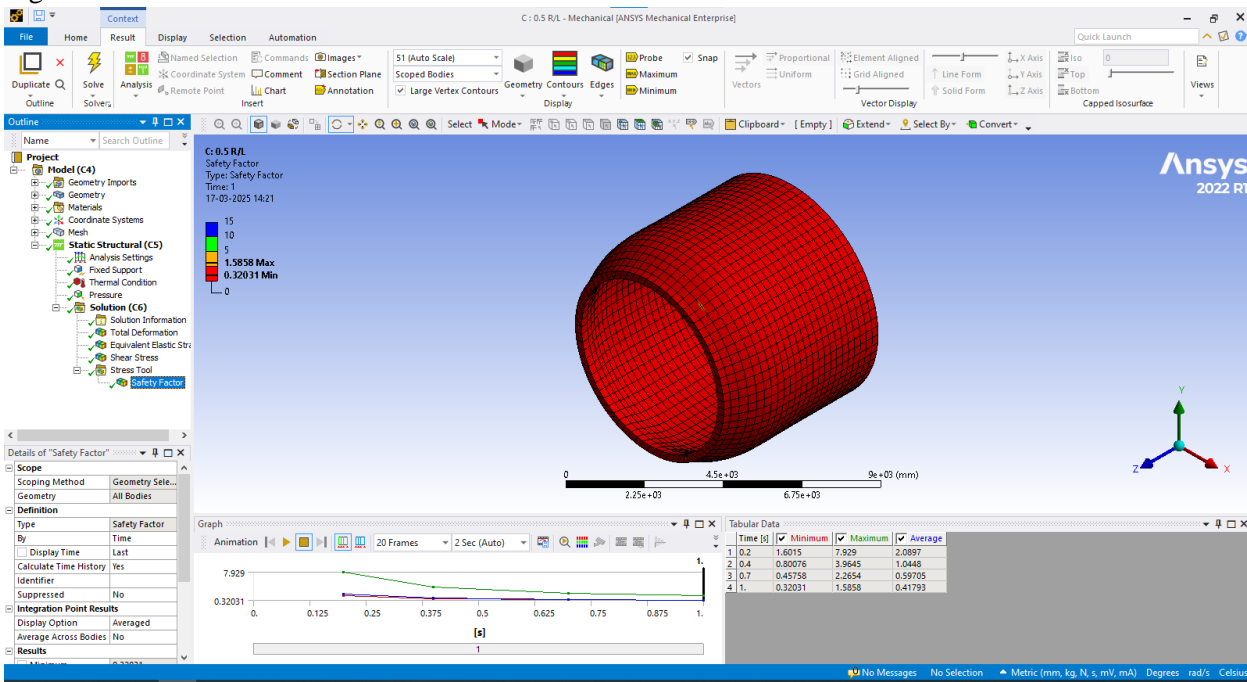


Fig 5.30 Safety Factor

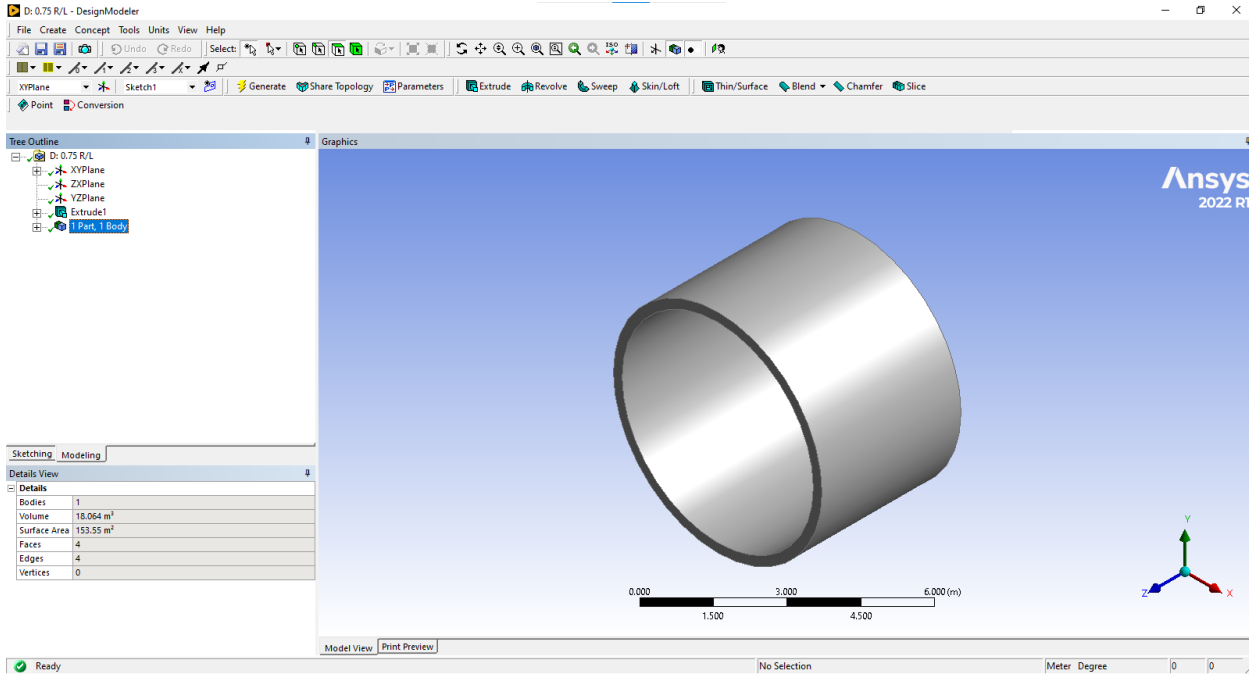


Fig 5.31 Isometric View

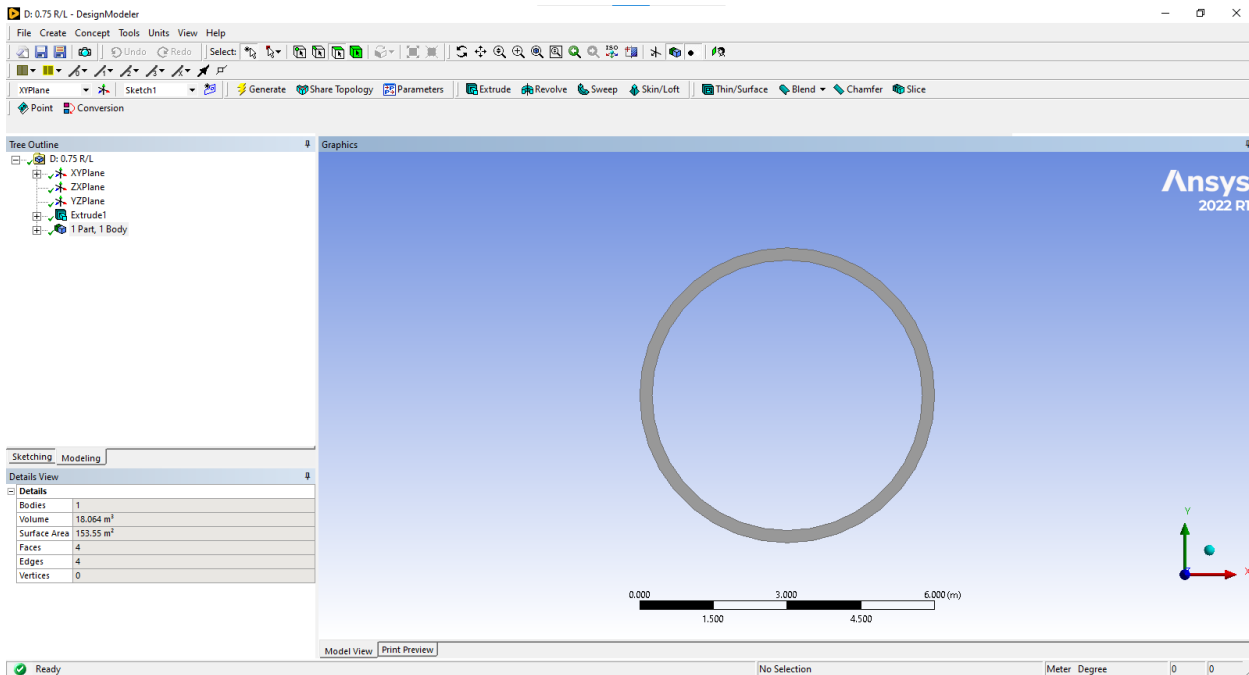


Fig 5.32 Front View

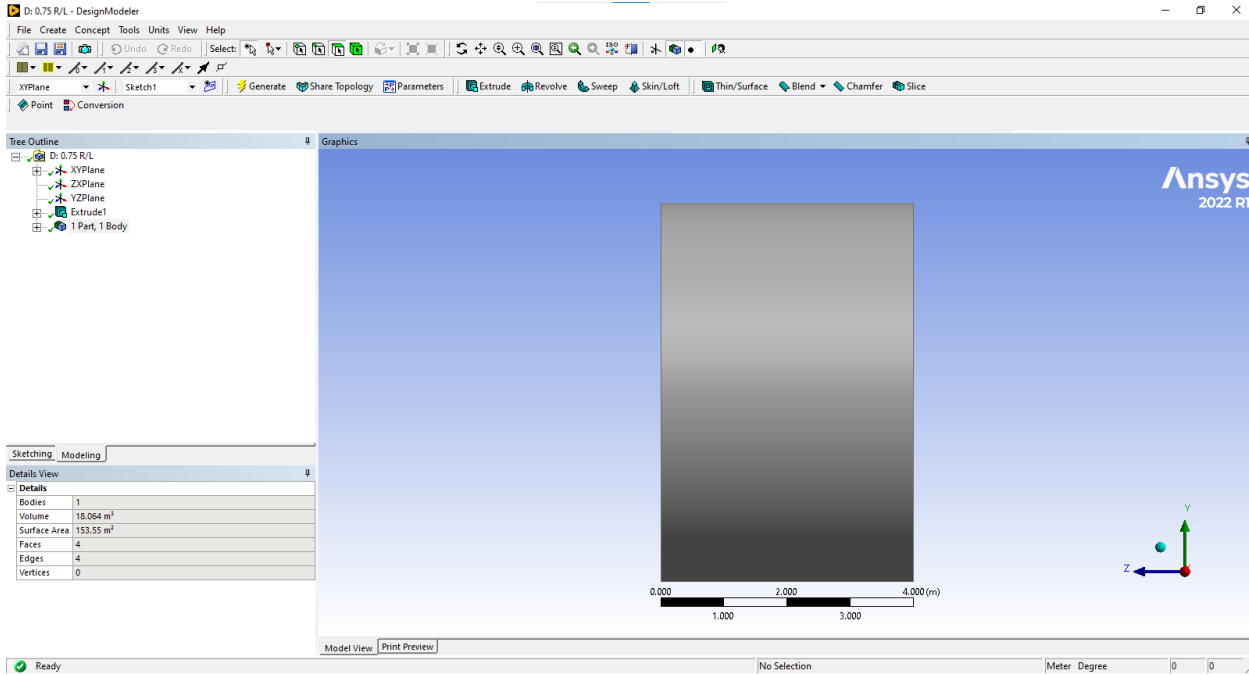


Fig 5.33 Side View

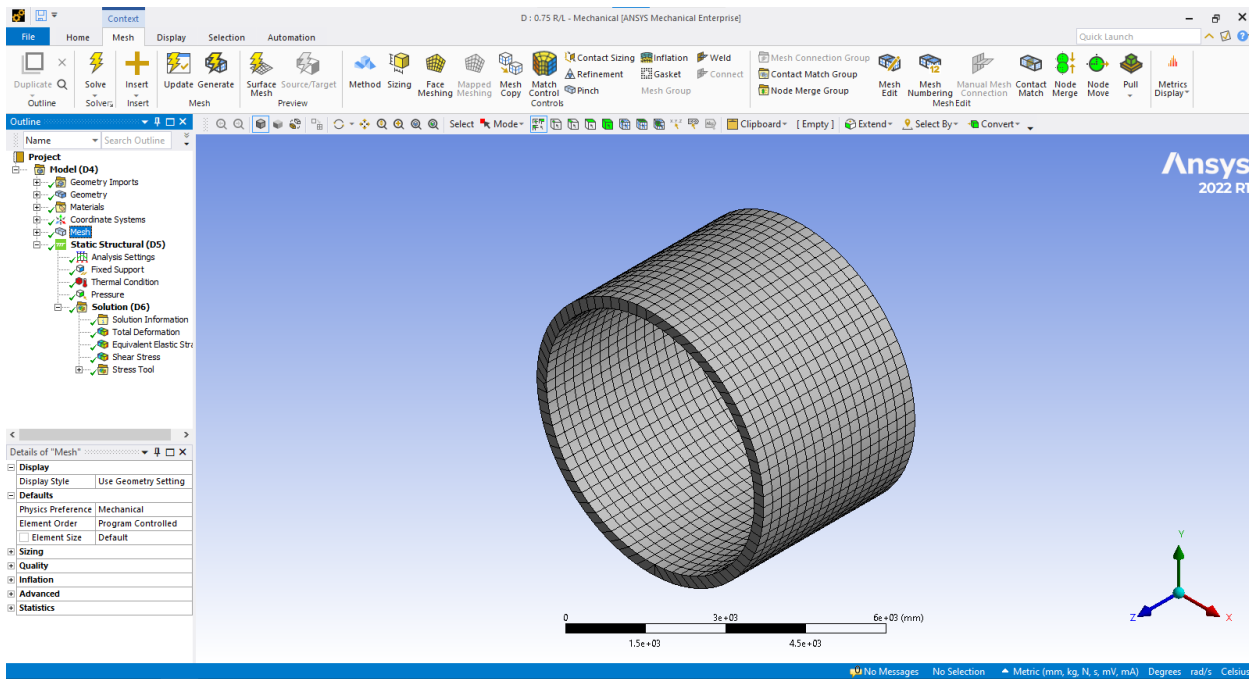


Fig 5.34 Meshing

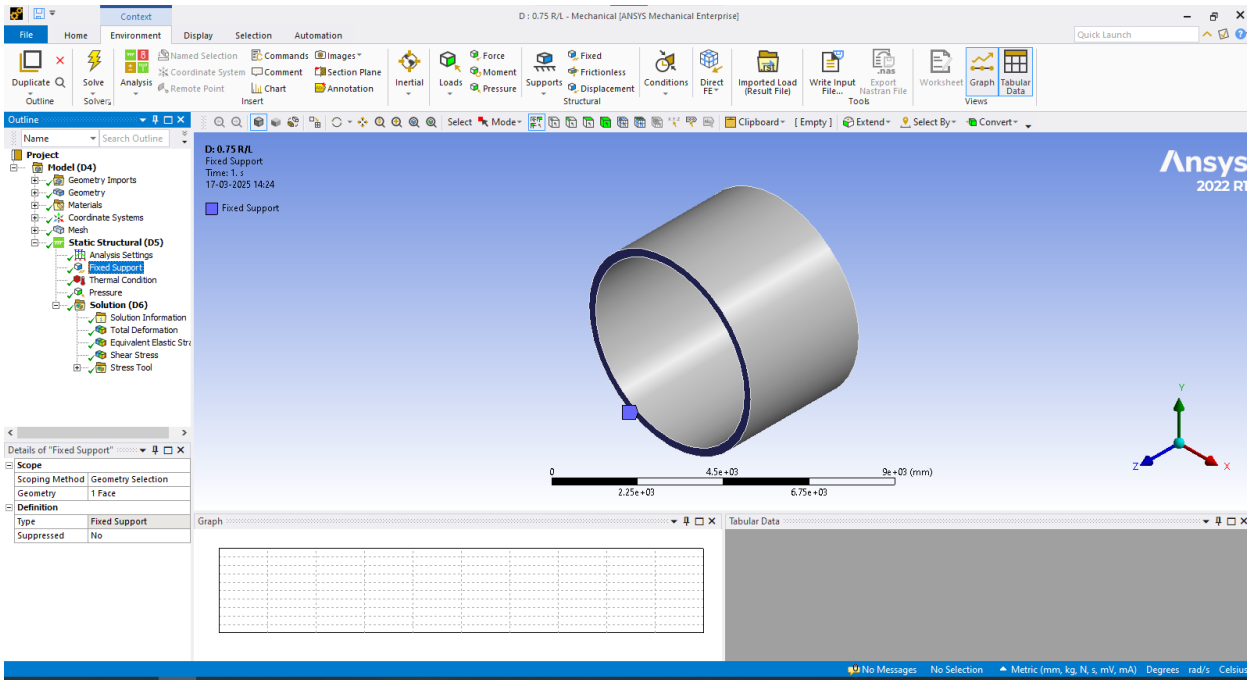


Fig 5.35 Fixed Support

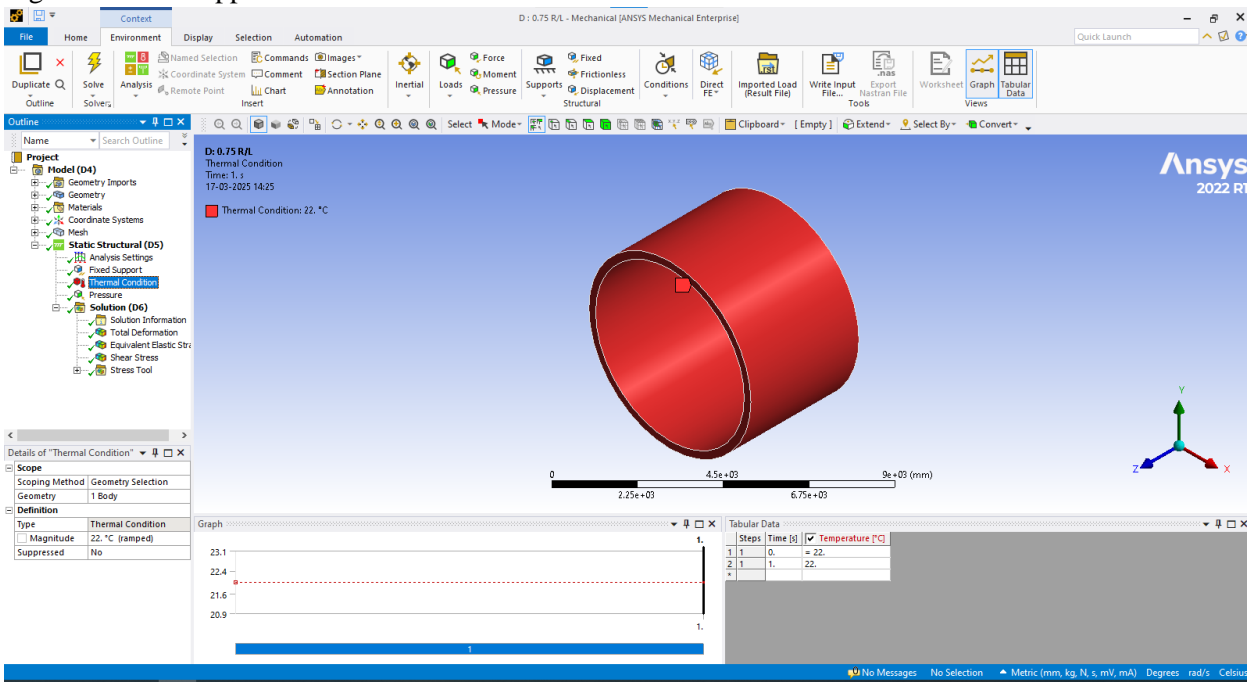


Fig 5.36 Thermal Condition

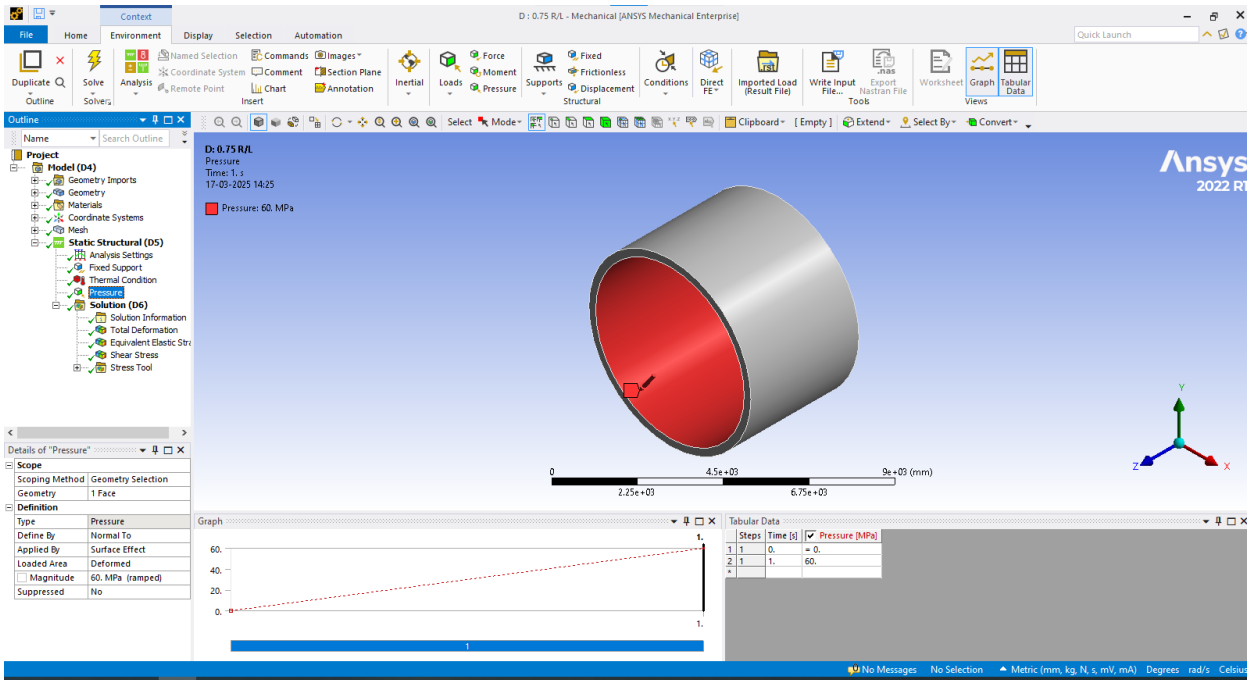


Fig 5.37 Internal Pressure

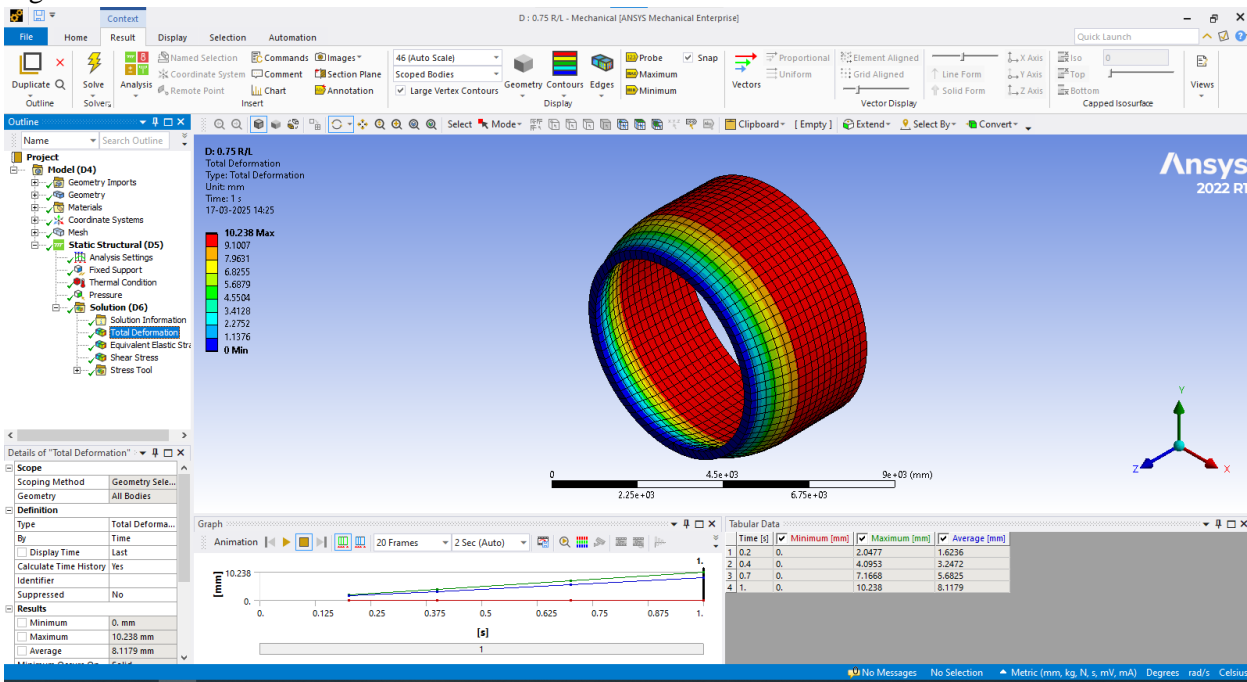


Fig 5.38 Total Deformation

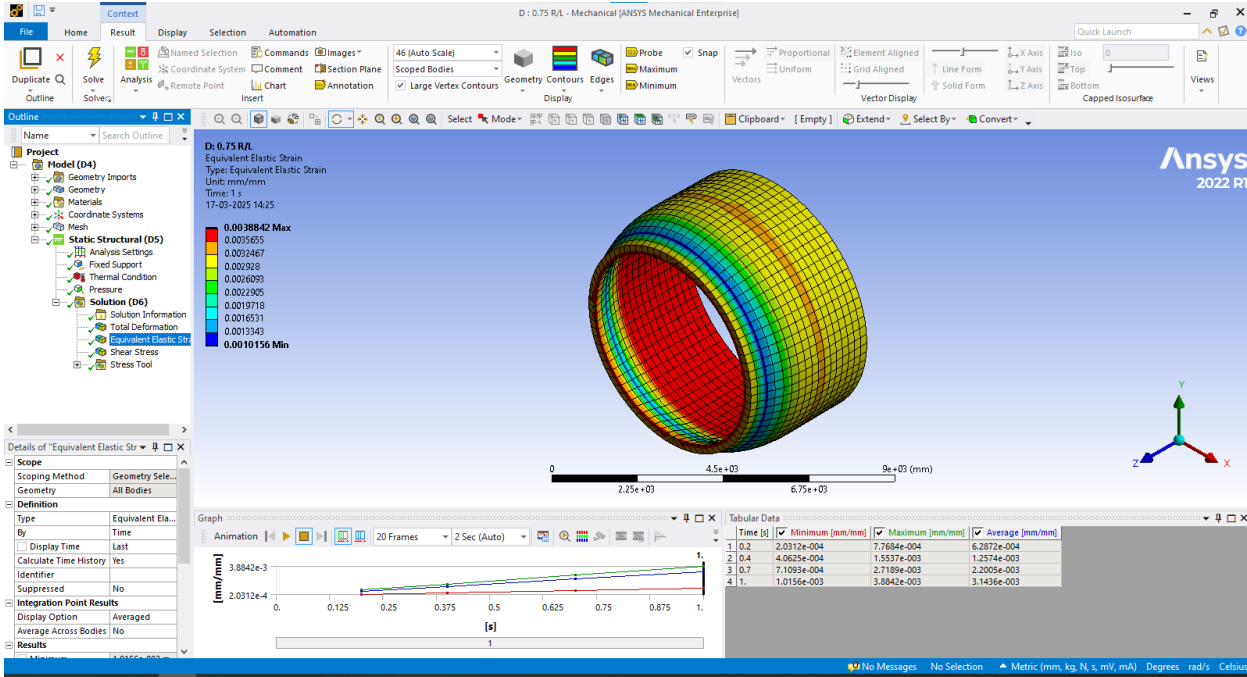


Fig 5.39 Equivalent Elastic Strain

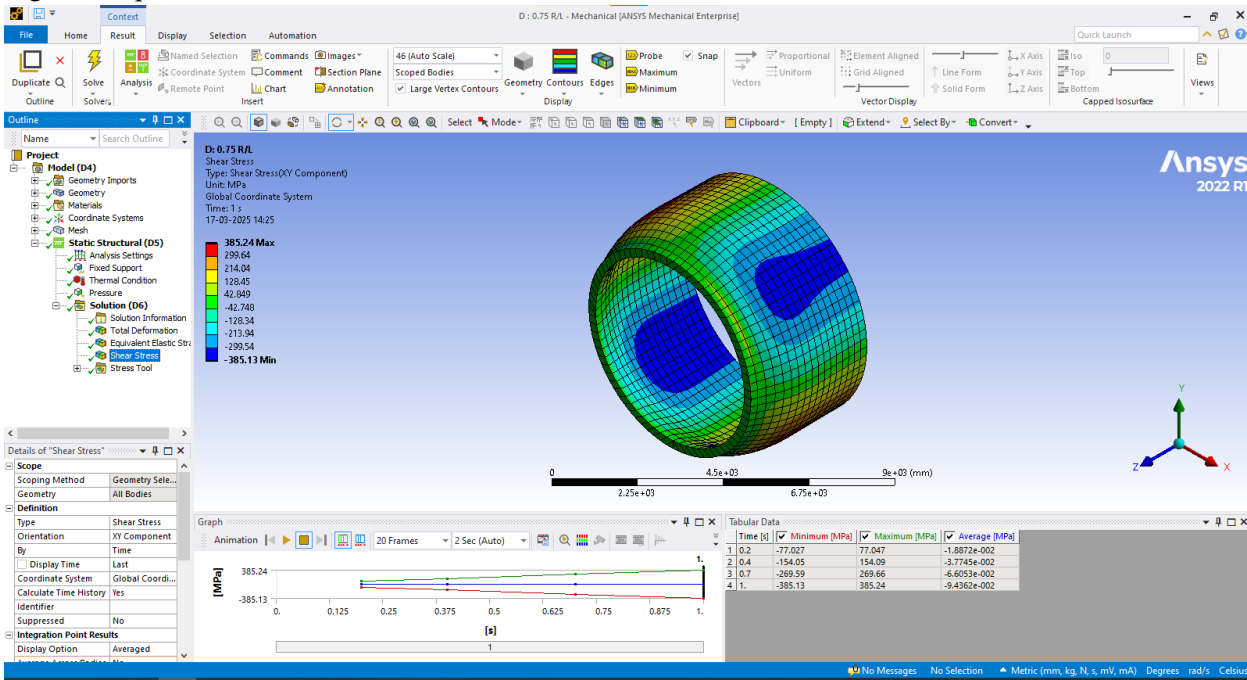


Fig 5.40 Shear Stress

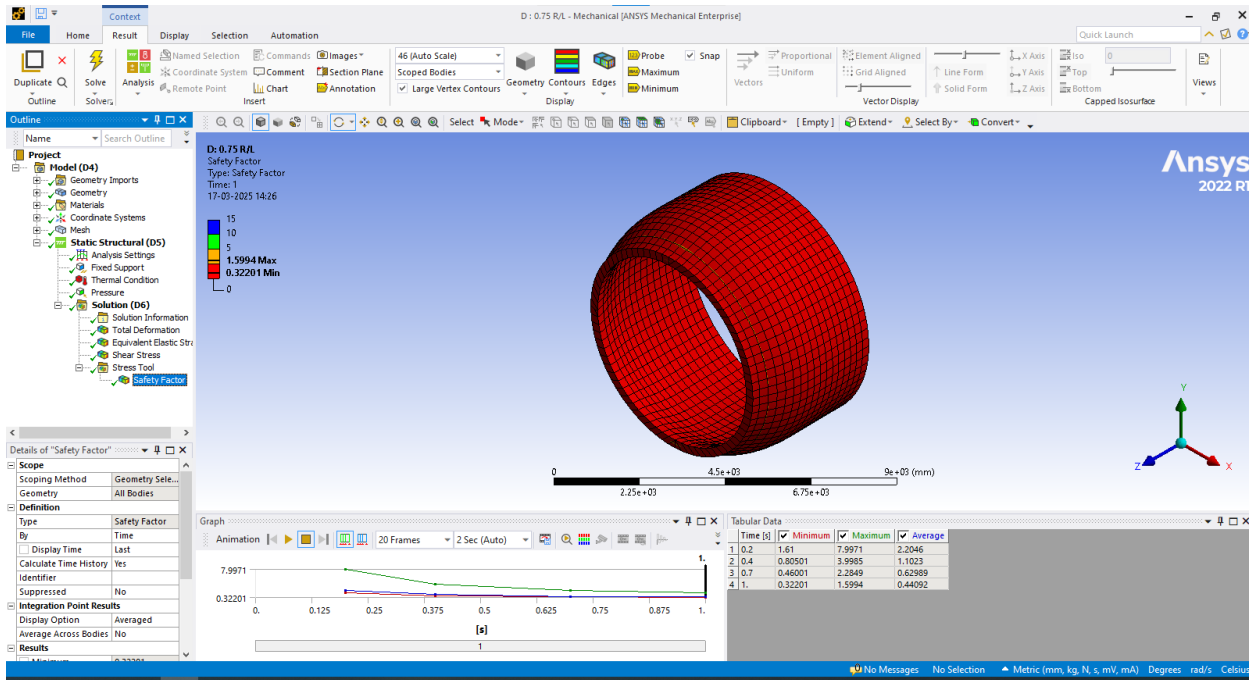


Fig 5.41 Safety Factor

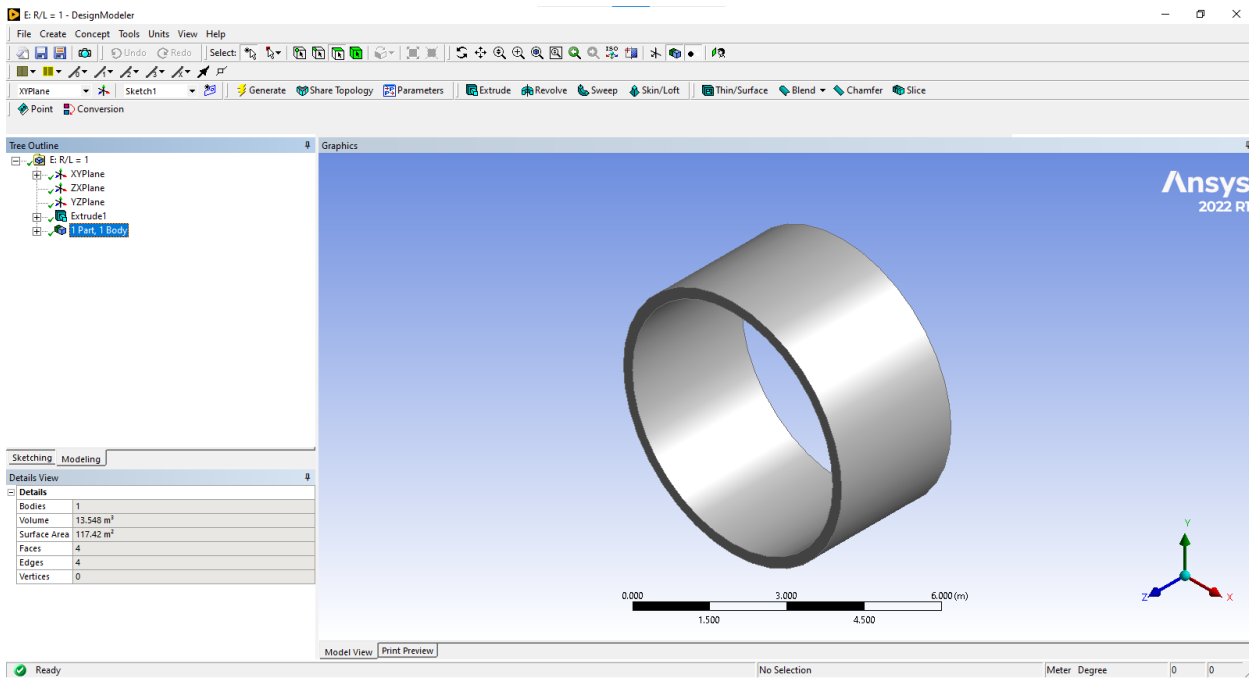


Fig 5.42 Isometric View

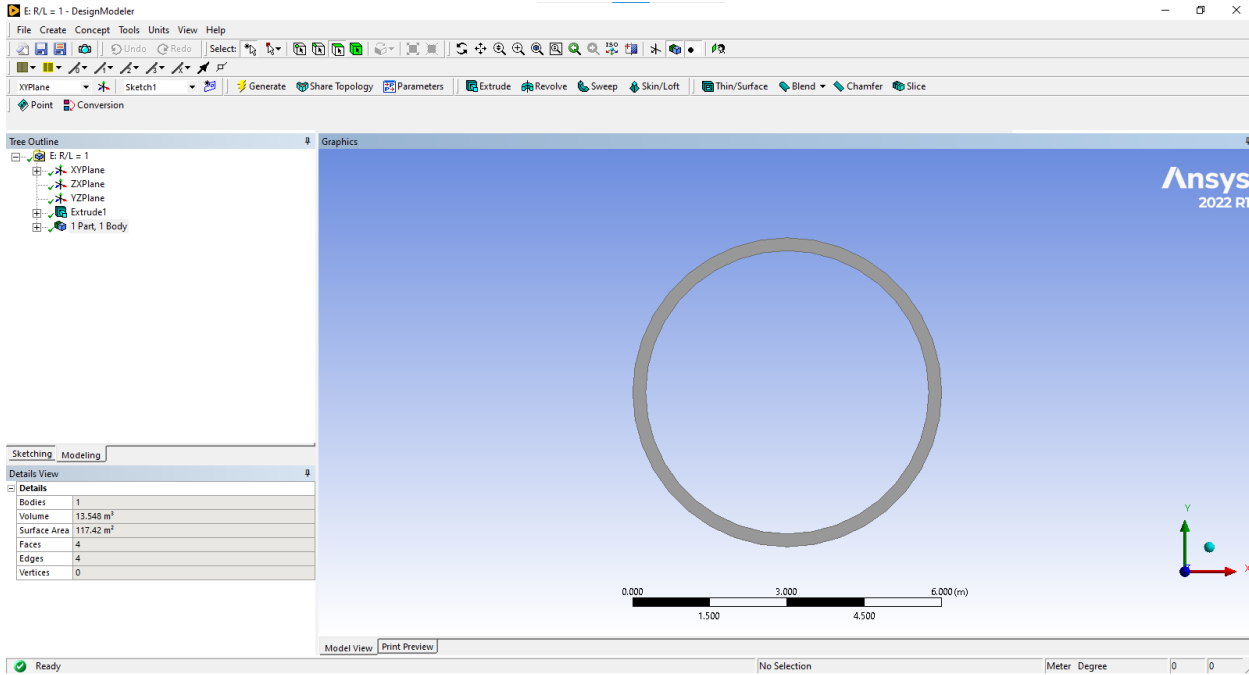


Fig 5.43 Front View

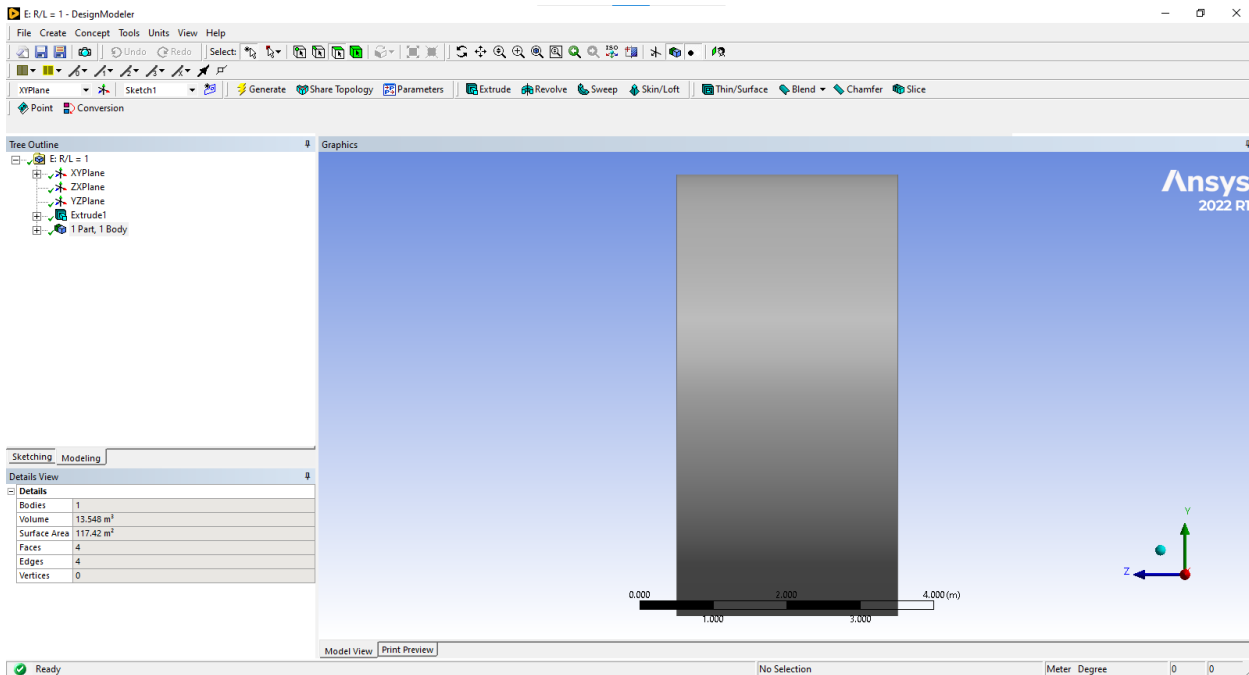


Fig 5.44 Side View

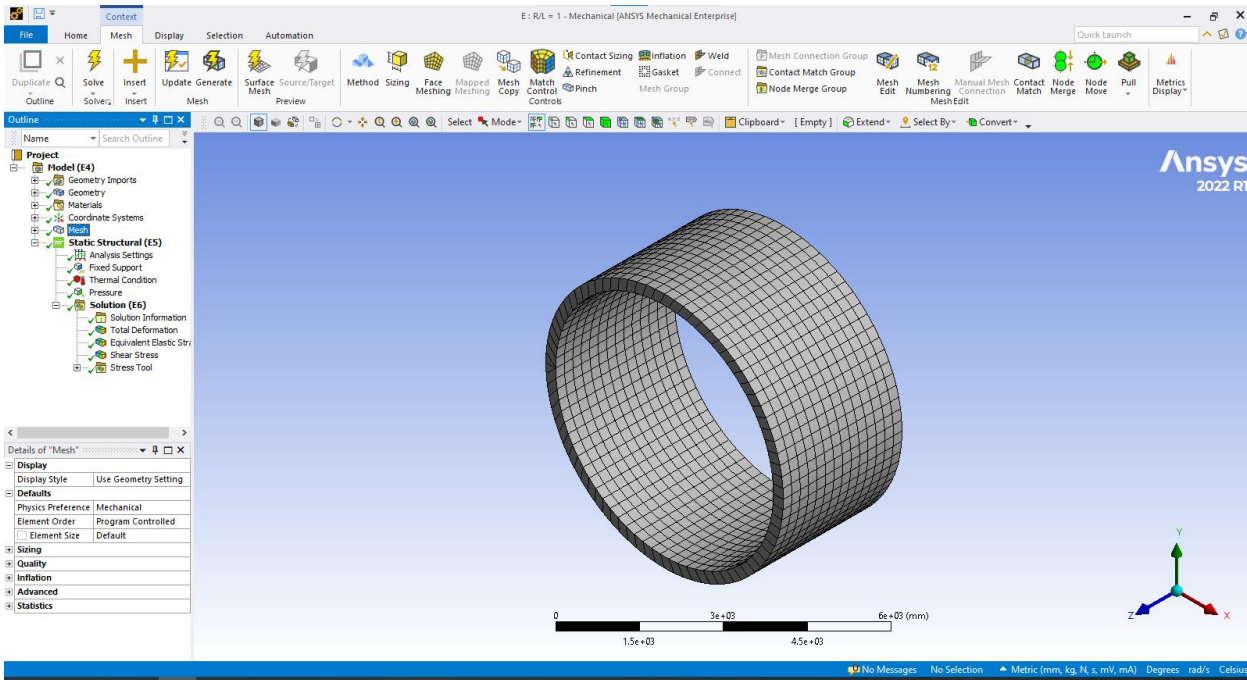


Fig 5.45 Meshing

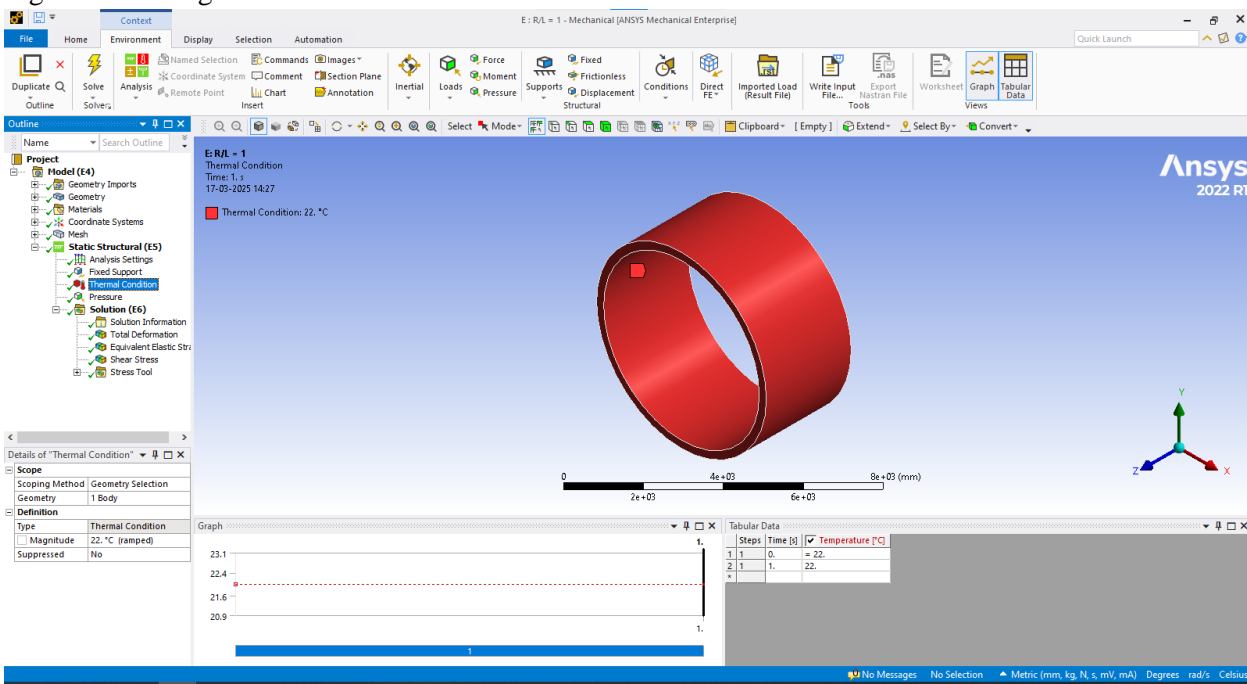


Fig 5.46 Thermal Condition

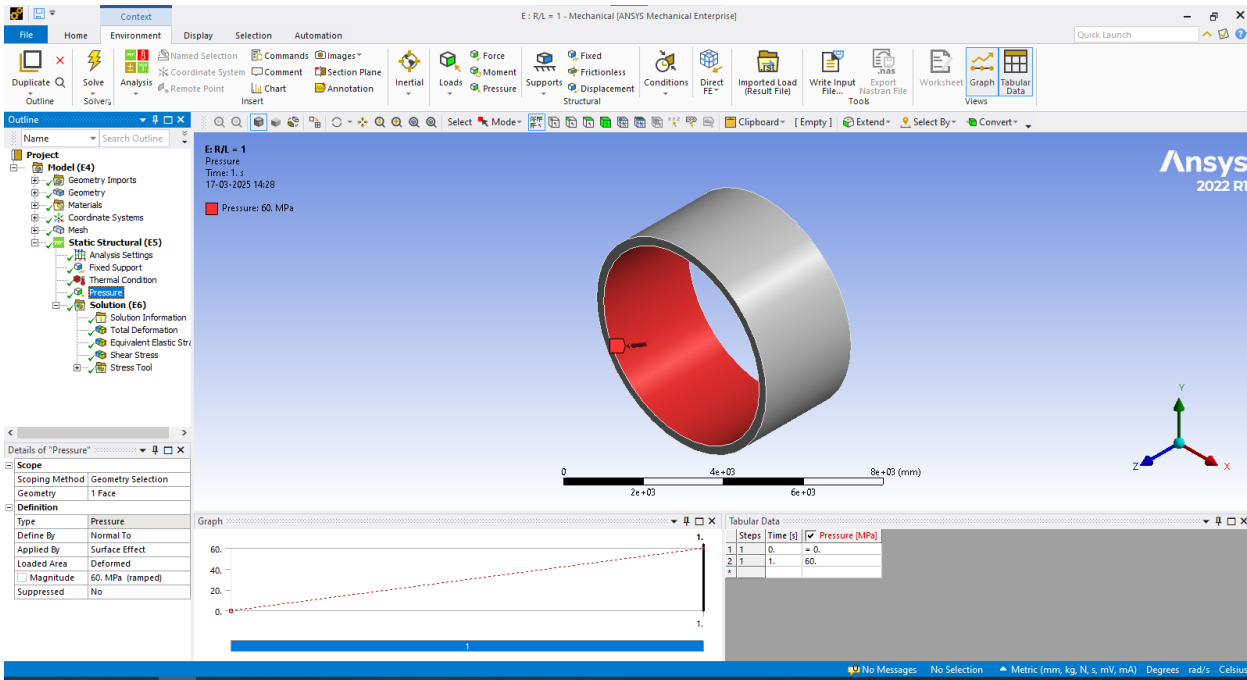


Fig 5.47 Internal Pressure

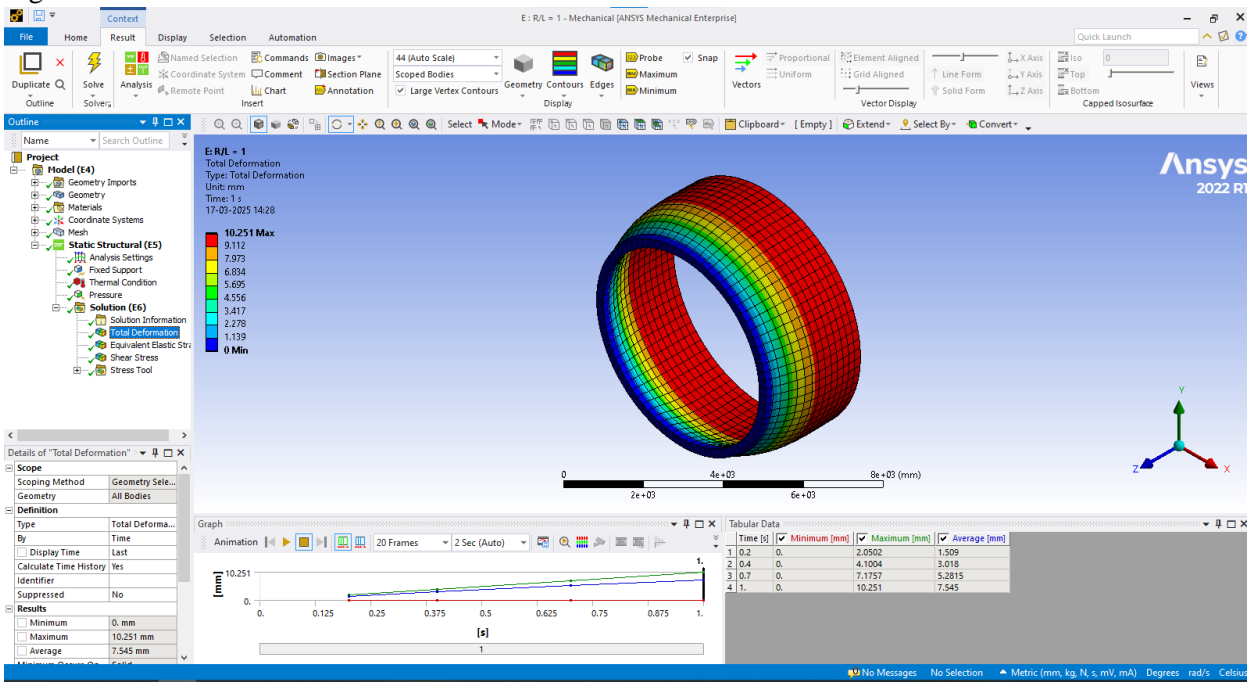


Fig 5.48 Total Deformation

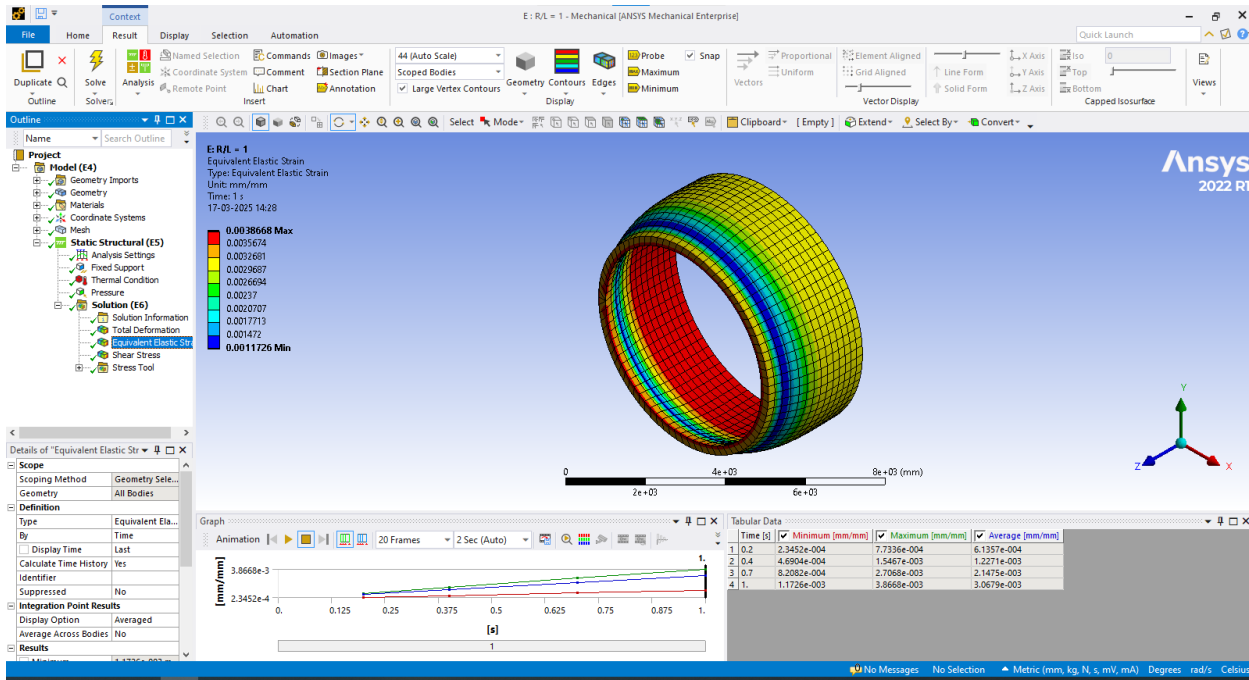


Fig 5.49 Equivalent Elastic Strain

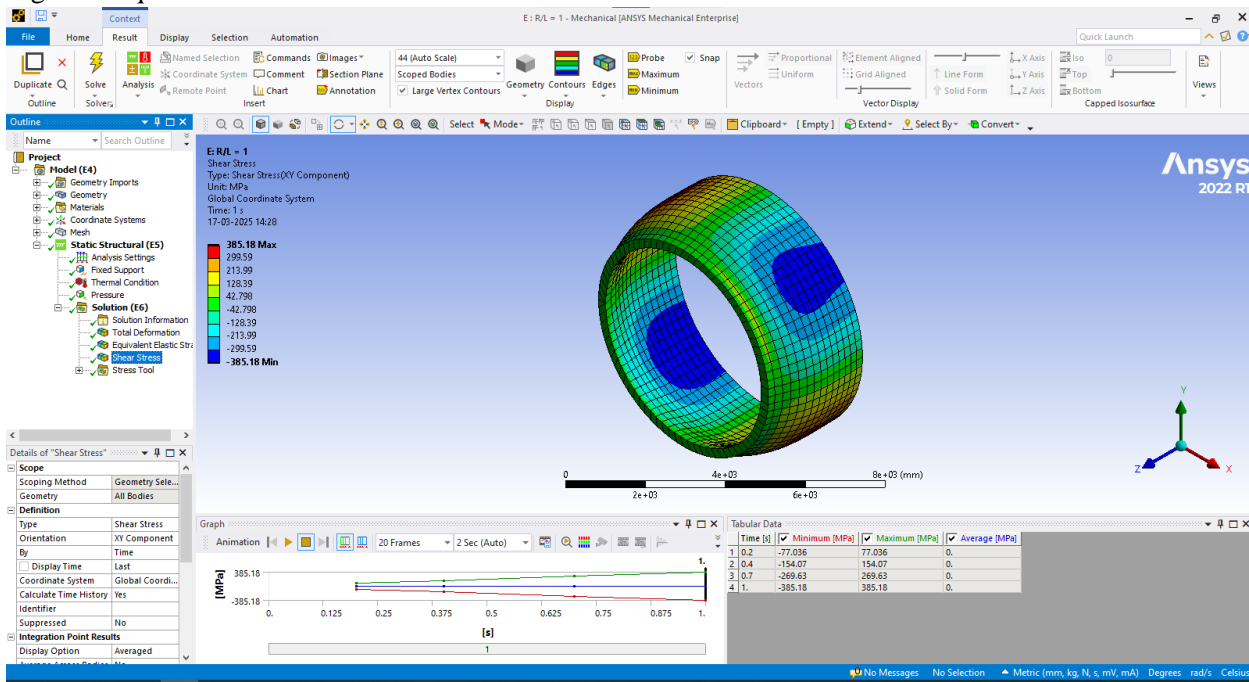


Fig 5.50 Shear Stress

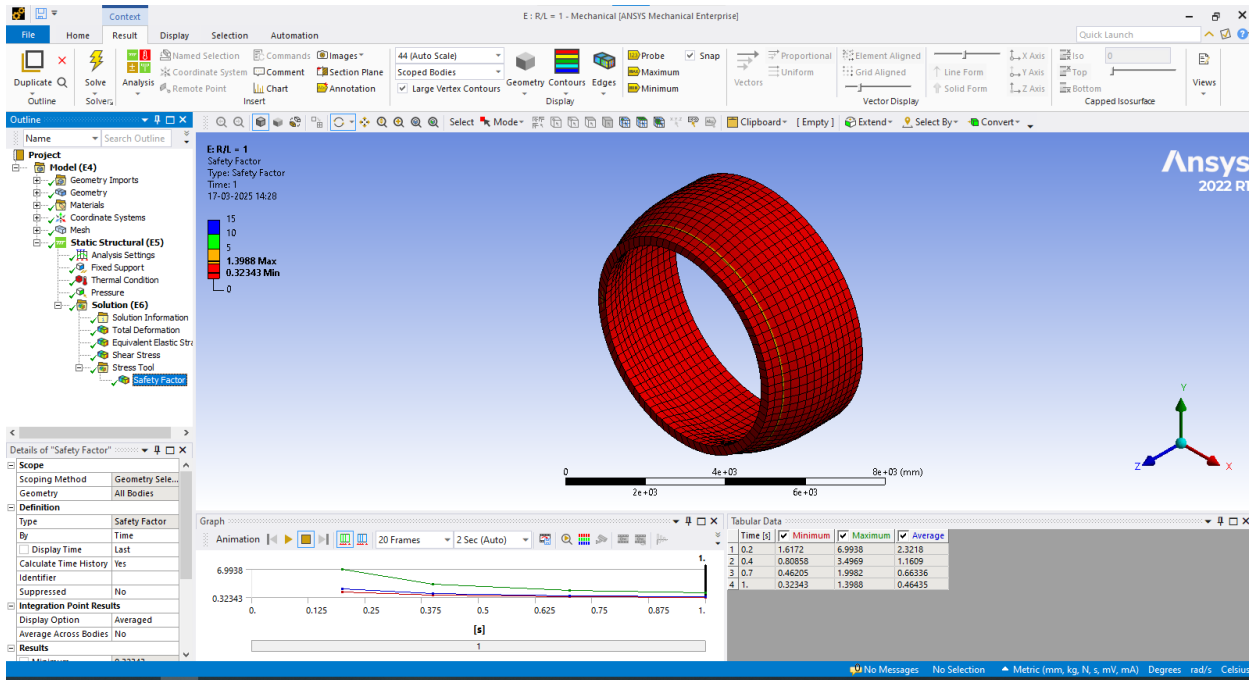


Fig 5.51 Safety Factor

CHAPTER – 6

CONCLUSION & FUTURE SCOPE

This project provides a comprehensive analysis of creep behavior in materials, with a specific focus on the time-dependent deformation of a hollow structural steel cylinder under sustained stress and elevated temperatures. By employing Norton's Power Law and utilizing ANSYS Workbench for simulation, the study successfully modeled the creep deformation of the cylinder, taking into account varying length-to-diameter ratios while maintaining fixed inner and outer diameters. The results highlight the significant influence of geometry, material properties, and loading conditions on creep behavior, offering valuable insights for the design and optimization of cylindrical structures in high-temperature applications.

Key findings from the analysis include:

1. Creep Deformation: The hollow cylinder exhibited predictable creep deformation over time, with radial displacement and axial elongation increasing as a function of applied stress, temperature, and material constants.
2. Length-to-Diameter Ratios: The study demonstrated that varying length-to-diameter ratios significantly impact the creep response, with longer cylinders experiencing greater axial elongation under the same loading conditions.
3. Material Behavior: The use of Norton's Power Law effectively captured the steady-state creep behavior of structural steel, providing a reliable framework for predicting long-term deformation in high-temperature environments.
4. Practical Implications: The findings underscore the importance of considering creep in the design of components such as turbine blades, pressure vessels, and structural elements in power plants, where materials are subjected to sustained stress and elevated temperatures.

The project also highlighted the critical role of material constants (C_1 , C_2 , C_3 , C_4) in creep modeling, emphasizing the need for accurate experimental determination of these parameters to ensure reliable predictions. Additionally, the integration of finite element analysis (FEA) tools like ANSYS Workbench proved invaluable for simulating complex geometries and boundary conditions, enabling a detailed understanding of creep behavior in real-world applications.

In conclusion, this study not only advances the understanding of creep deformation in hollow cylindrical structures but

also provides a practical methodology for evaluating and mitigating creep in engineering designs. By addressing the effects of geometry, material properties, and loading conditions, this work contributes to the development of safer and more efficient high-temperature components, ensuring their long-term performance and reliability. Future work could explore the effects of additional factors such as thermal gradients, cyclic loading, and material degradation to further enhance the accuracy of creep predictions.

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