Fracture Analysis of Hollow Cylinder

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Abstract:
This study presents a comprehensive fracture analysis of a hollow cylinder subjected to axial loading. The cylinder's material properties and geometric parameters, such as inner and outer radii, are considered. Using finite element analysis (FEA) and linear elastic fracture mechanics (LEFM), the stress intensity factors (SIFs) are calculated for various crack lengths and orientations. The results show that the SIFs increase with crack length and decrease with increasing inner radius. The critical crack length for fracture initiation is determined, and the effects of cylinder geometry and material properties on fracture behavior are discussed. This research provides valuable insights into the fracture mechanics of hollow cylinders, which is essential for designing and optimizing structural components in various engineering applications.

Keywords
Fracture analysis, Hollow cylinder, Axial loading, Finite element analysis, Linear elastic fracture mechanics, Stress intensity factors.

1. *INTRODUCTION*

Fracture analysis is a critical aspect of materials science and engineering, particularly in the context of structural integrity and safety. It involves the study of the initiation and propagation of cracks in materials under various loading conditions. Understanding fracture mechanics is essential for predicting the failure of components, especially in applications where safety is paramount, such as in aerospace, automotive, and civil engineering structures. Among various geometries, hollow cylinders are widely used in numerous engineering applications, including pipelines, pressure vessels, and structural supports. This introduction aims to provide a comprehensive overview of the significance of fracture analysis in hollow cylinders, the underlying principles of fracture mechanics, and the methodologies employed in such analyses.

Fundamentals of Fracture Mechanics

Fracture mechanics is the field of study that focuses on the behavior of materials containing cracks. It provides the theoretical framework for understanding how cracks initiate, grow, and ultimately lead to failure. The fundamental concepts of fracture mechanics can be categorized into two primary approaches: linear elastic fracture mechanics (LEFM) and elastic-plastic fracture mechanics (EPFM).

1. **Linear Elastic Fracture Mechanics (LEFM)**: LEFM is applicable to brittle materials where the material behavior can be described by linear elasticity. In this framework, the stress intensity factor (K) is a critical parameter that characterizes the stress state near the crack tip. The relationship between the applied stress and the crack length is described by the following equation:

$$K = \sigma\sqrt{\pi a}$$

Where:

- K is the stress intensity factor,
- σ is the applied stress,
- a is the crack length.

The critical stress intensity factor, known as the fracture toughness (Kc), defines the material's resistance to crack propagation. If the applied stress intensity factor exceeds the material's fracture toughness, crack propagation will occur, leading to failure.

2. **Elastic-Plastic Fracture Mechanics (EPFM)**: EPFM is used for ductile materials where plastic deformation occurs before fracture. In this approach, the J-integral is a key parameter that characterizes the energy release rate associated with crack growth. The J-integral accounts for both elastic and plastic deformations and is defined as:

$$J = \int_C \left(W\,dy - \sigma \frac{du}{dy}\,dx\right)$$

Where:

- W is the strain energy density,
- σ is the stress,
- u is the displacement,
- C is the contour around the crack tip.

The J-integral provides a more comprehensive understanding of crack behavior in ductile materials, allowing for the prediction of crack growth under various loading conditions.

OBJECTIVE:

- **Stress Distribution and Concentration**: Determine how stresses are distributed around the crack tip, especially in regions of high stress concentration (e.g., near the crack tip or the boundaries of the hollow cylinder).
- **Crack Propagation**: Investigate the growth and propagation of semi-elliptical cracks under various loading conditions (tensile, compressive, or bending).
- **Fracture Toughness and Fatigue**: Calculate the fracture toughness of the material by analyzing the stress intensity factors (SIF) for the semi-elliptical crack. This helps in predicting the critical crack size at which failure occurs.
- **Critical Load Prediction**: Determine the critical load or stress at which the hollow cylinder will fail, based on the growth of the semi-elliptical crack.

METHODOLOGY:

STRUCTURAL STEEL MATERIAL PROPERTIES :

Mechanical Properties

- **Young's Modulus (E)**: 210 GPa (30,000,000 psi)
- **Poisson's Ratio (ν)**: 0.3
- **Yield Strength (σy)**: 250-350 MPa (36,000-50,000 psi)
- **Ultimate Tensile Strength (σu)**: 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/hft°F)
- **Specific Heat Capacity (c)**: 500-600 J/kgK (0.12-0.14 Btu/lb°F)
- **Thermal Expansion Coefficient (α)**: 12-15 × 10^(-6) K^(-1) (6.7-8.3 × 10^(-6) °F^(-1))

Creep Properties

- **Creep Constant (A)**: 1.0e-10 (1/s)
- **Stress Exponent (n)**: 3.5
- **Time Exponent (m)**: 0.5

Other Properties

- **Density (ρ)**: 7850 kg/m^3 (490 lb/ft^3)
- **Corrosion Resistance**: Moderate to high, depending on the specific alloy and environmental conditions.

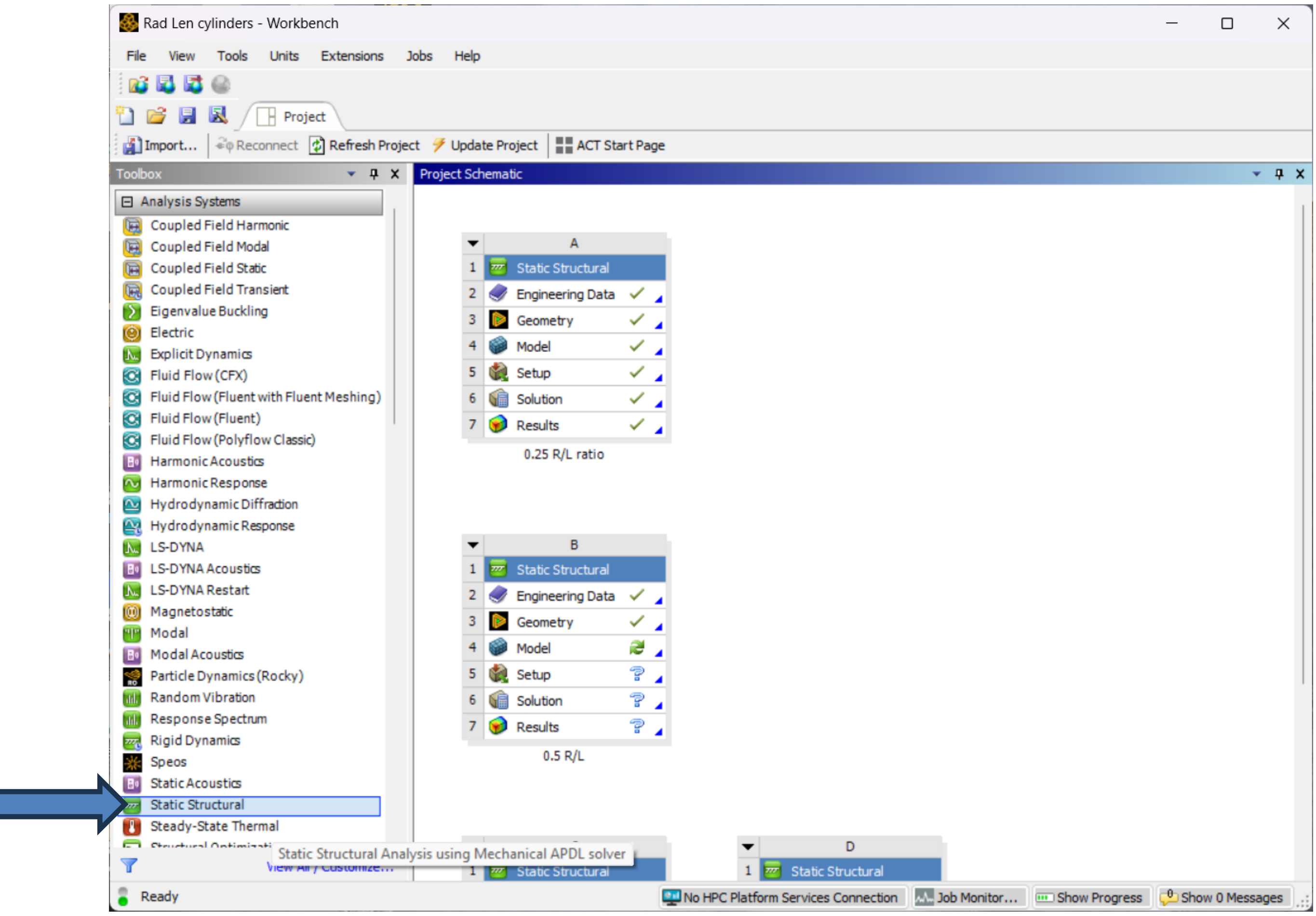
Note that these values are approximate and can vary depending on the specific type of structural steel, its composition, and the manufacturing process. Additionally, some properties may be affected by factors such as temperature, strain rate, and loading conditions.

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%

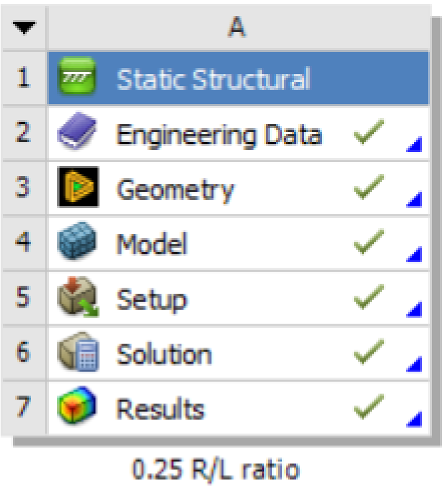
1. Geometry Creation

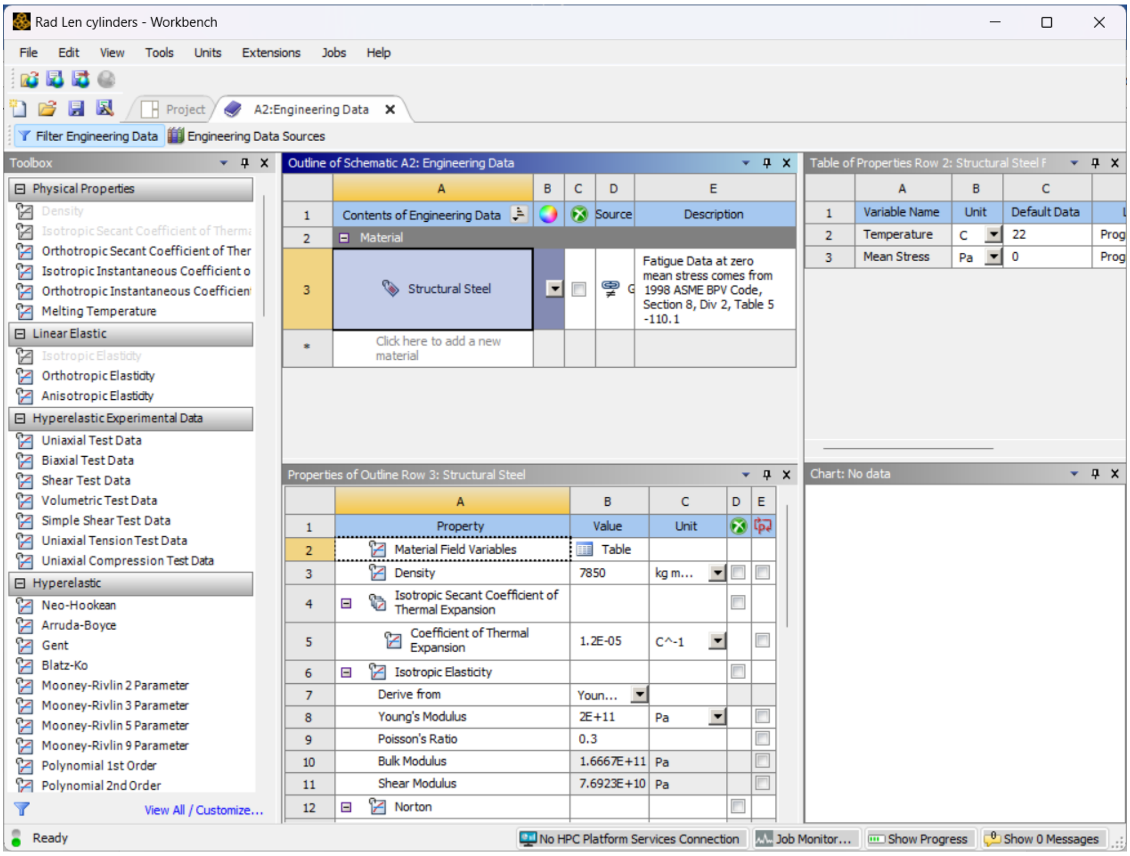
- **Open ANSYS Workbench**:
- Start a new project and select the "Static Structural" template.



Define material properties :

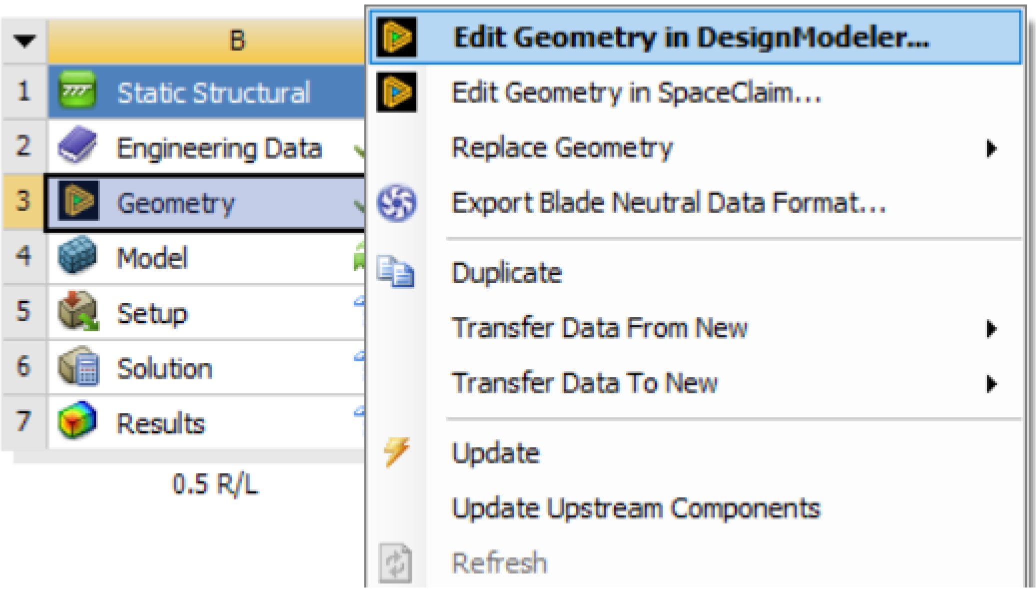
In engineering data apply all related properties regarding specification of structural steel.



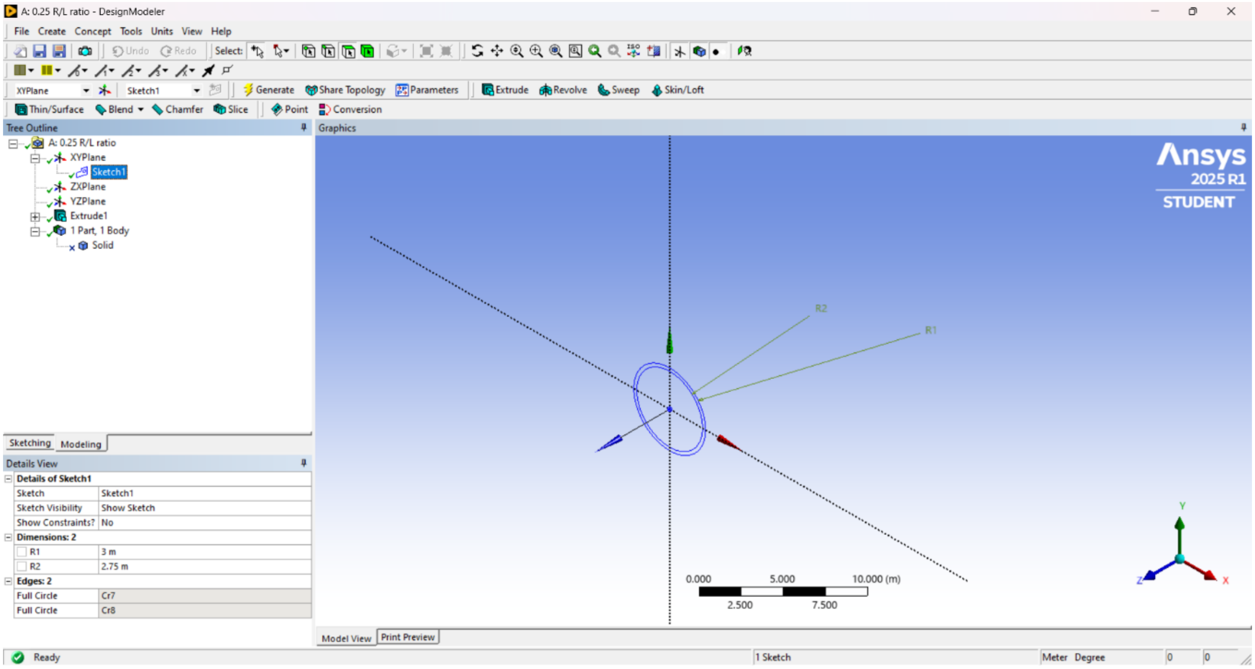


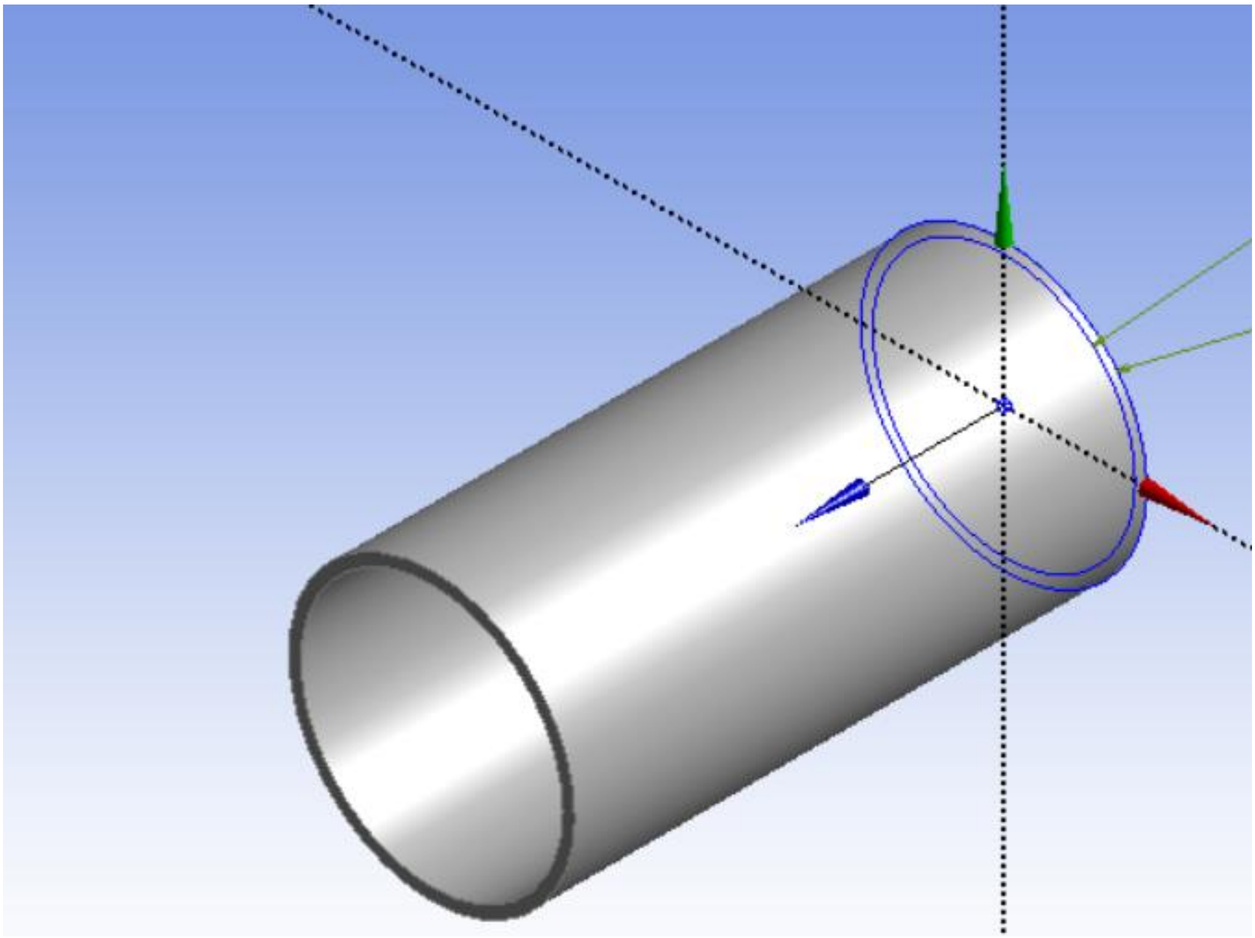
GEOMETRY:

Based on required geometry the cylinder is formed through design modeler

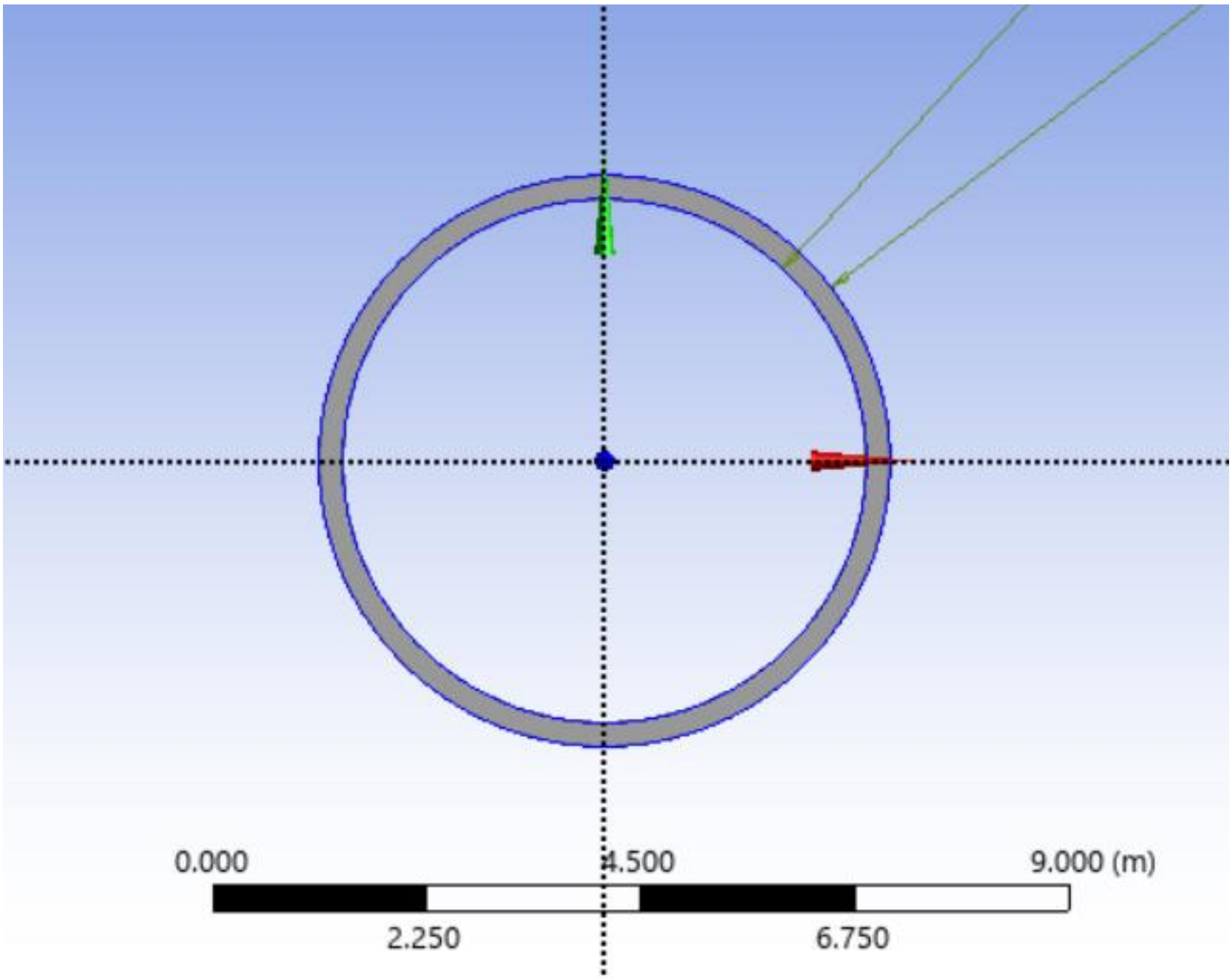


The cylinder is designed based on specified ratio of
Radius
and
length

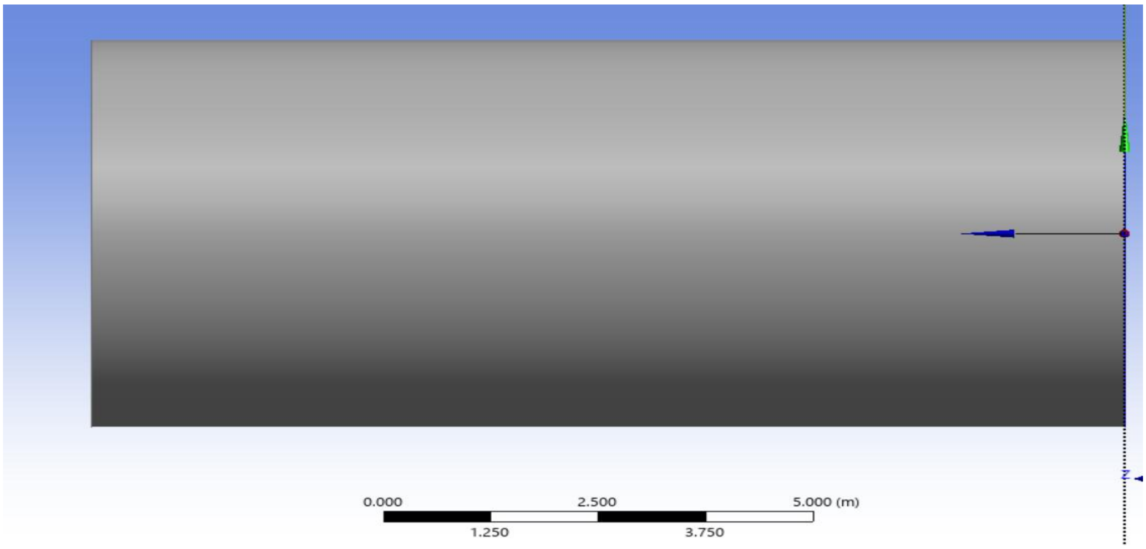




ISOMETRIC VIEW

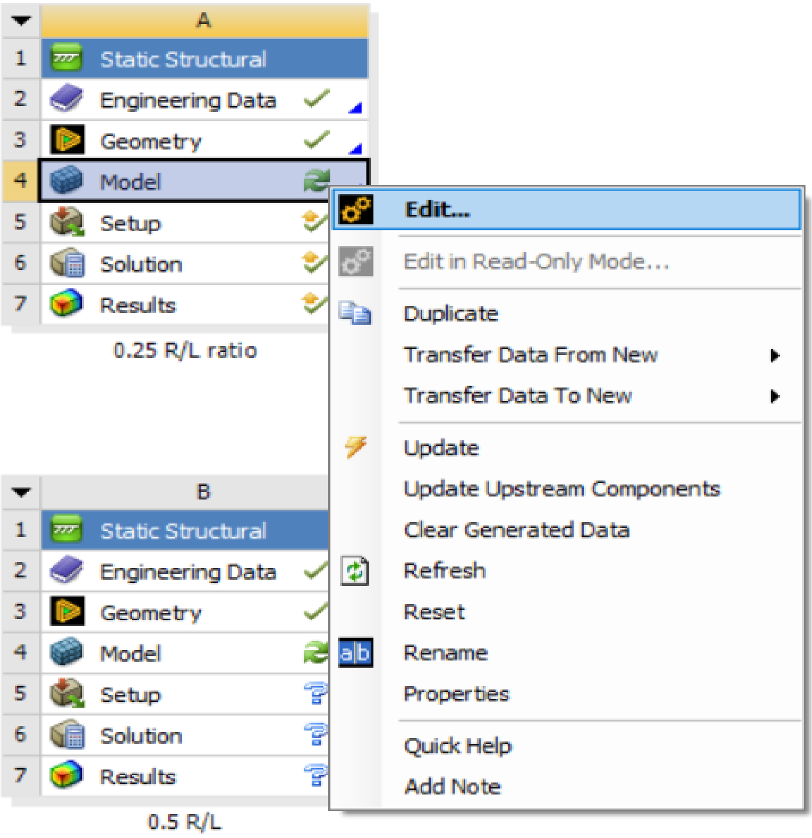


FRONT VIEW

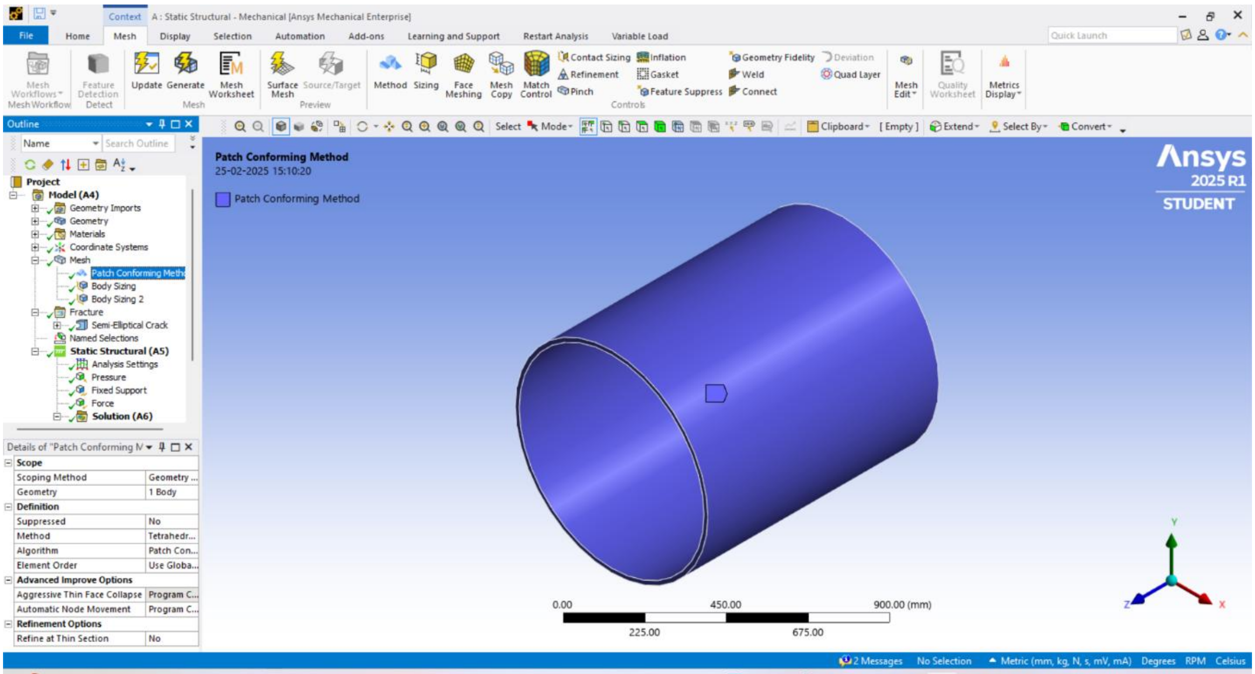


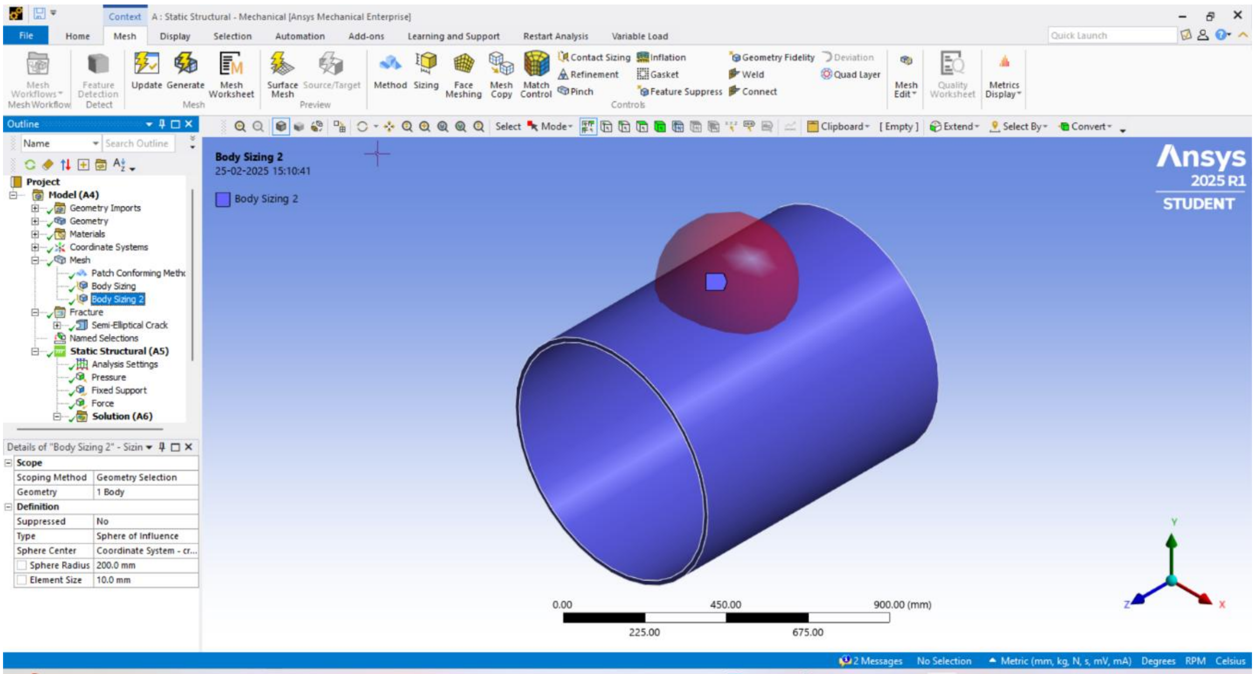
SIDE VIEW

TOP VIEW



Meshing


A : Static Structural - Mechanical [Ansys Mechanical Enterprise]
Patch Conforming Method
25-02-2025 15:10:20
Patch Conforming Method
Ansys
2025 R1
STUDENT
0.00
450.00
900.00 (mm)
225.00
675.00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Body Sizing 2
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Body Sizing 2
Ansys
2025 R1
STUDENT
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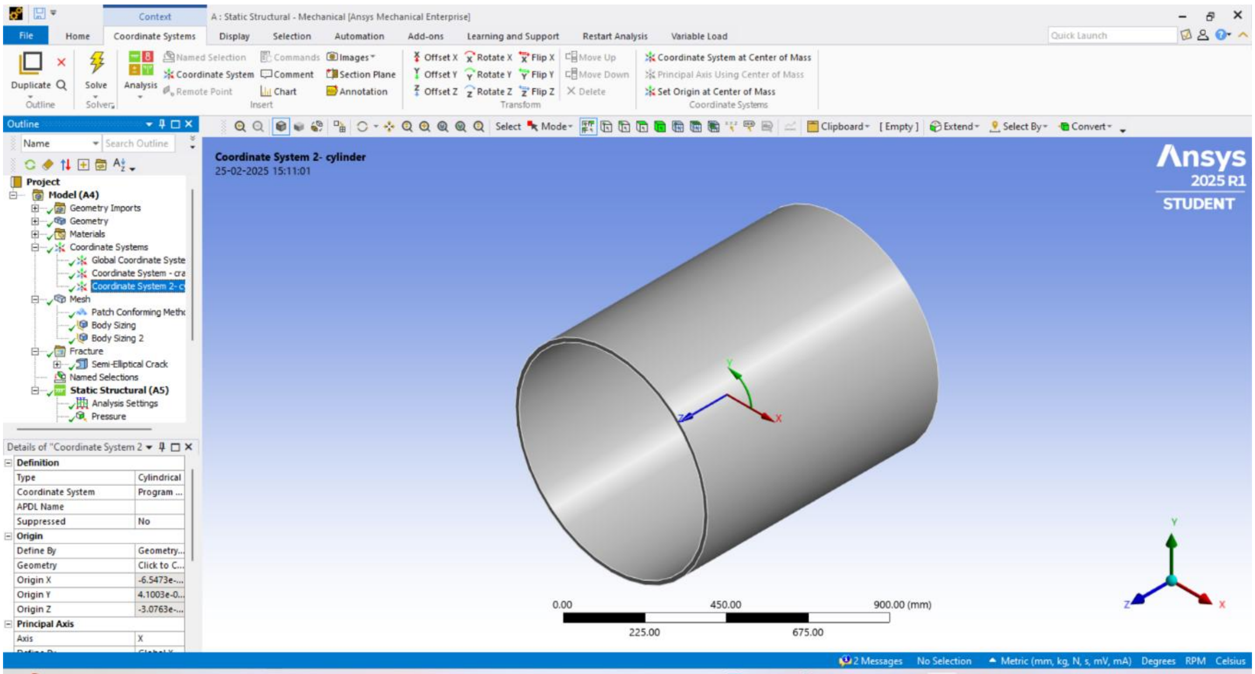
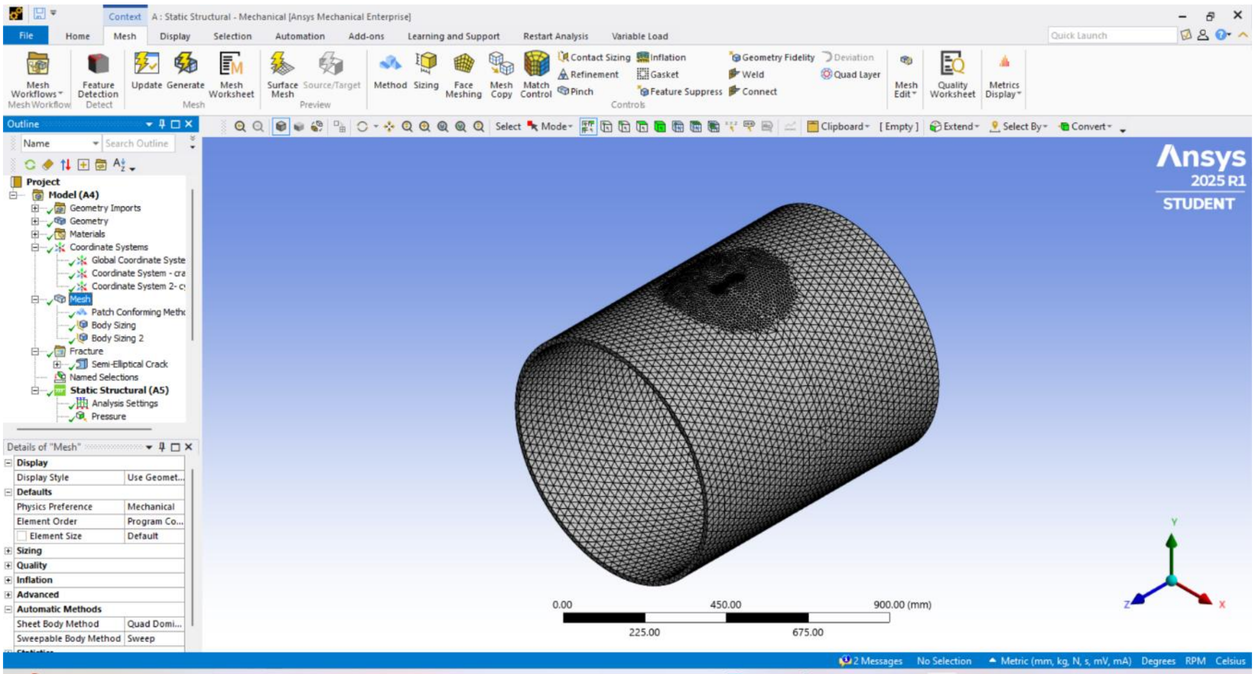
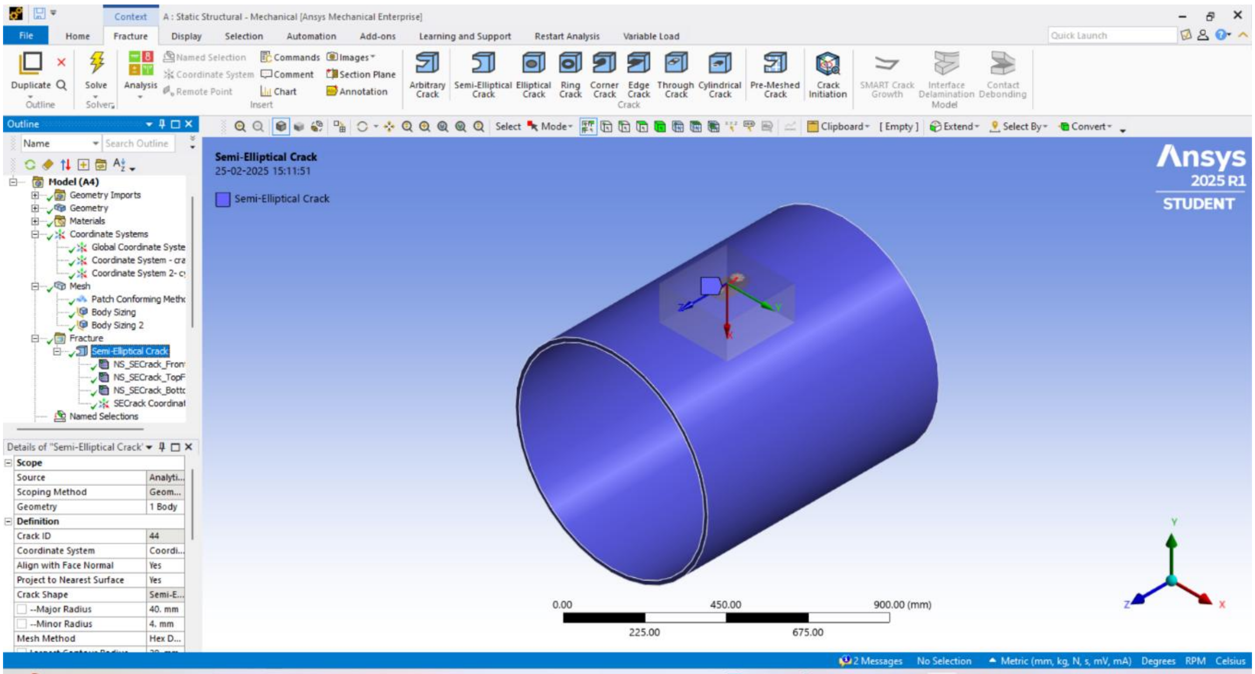
225.00
675.00





Insertion semi-elliptical crack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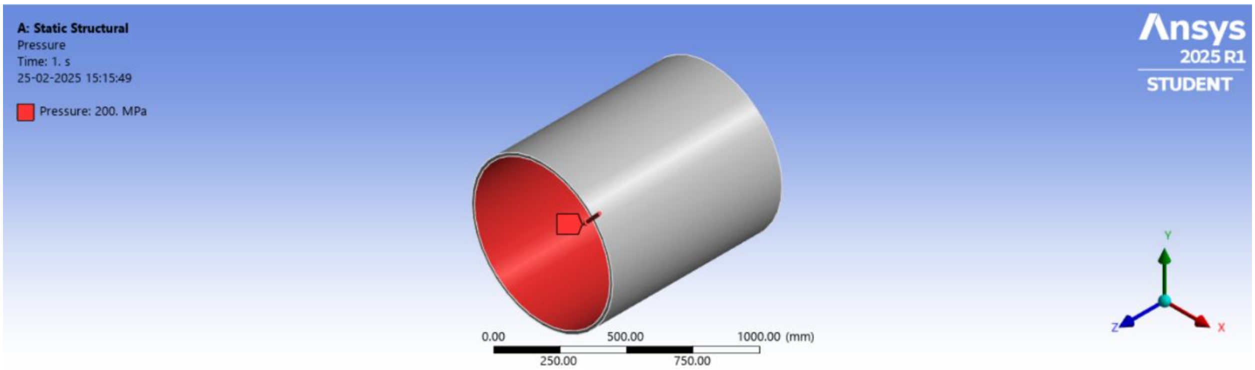
Semi-Elliptical Crack
25-02-2025 15:11:51
Semi-Elliptical Crack
Ansys
2025 R1
STUDENT
Details of "Semi-Elliptical Crack"
Scope
Source
Scoping Method
Geometry
1 Body
Definition
Crack ID
44
Coordinate System
Align with Face Normal
Yes
Project to Nearest Surface
Yes
Crack Shape
--Major Radius
40. mm
--Minor Radius
4. mm
Mesh Method
0.00
450.00
900.00 (mm)
225.00
675.00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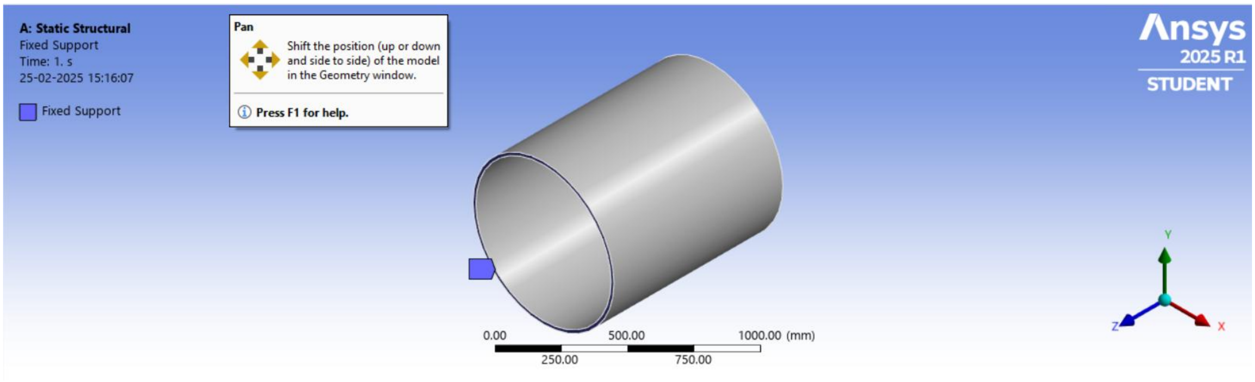
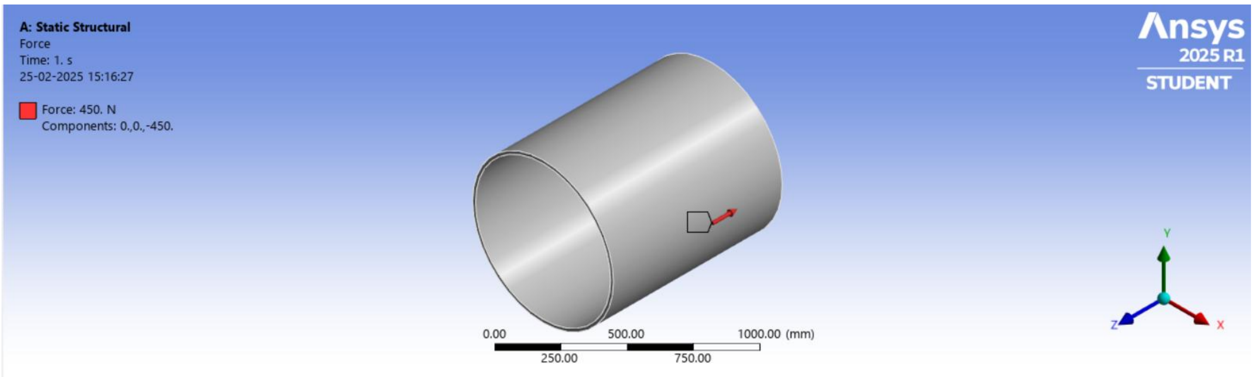
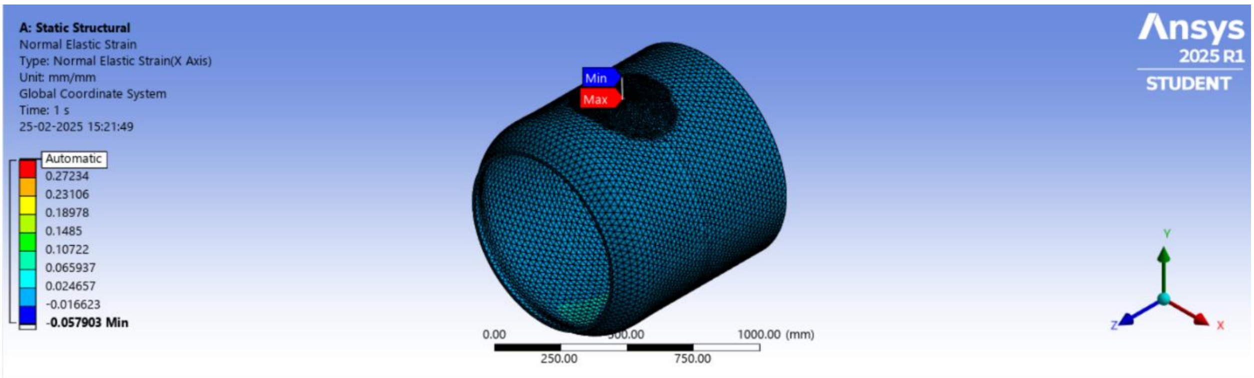
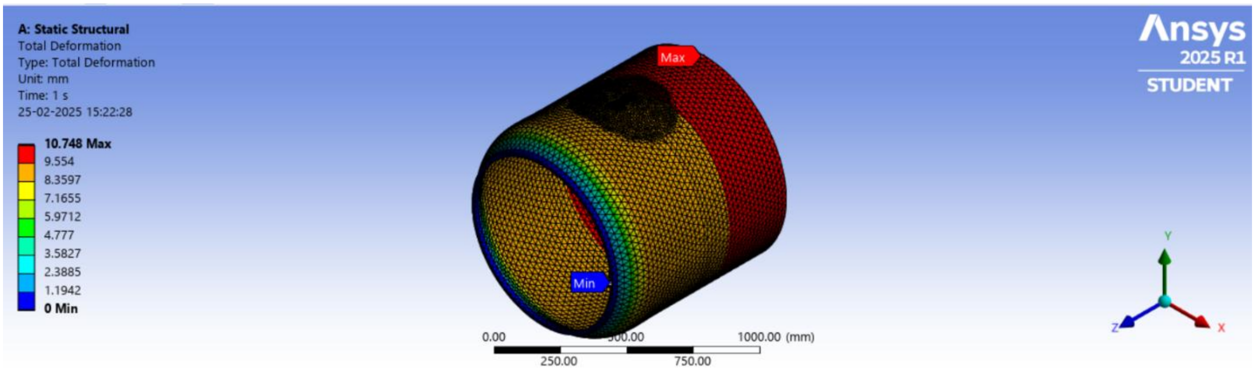
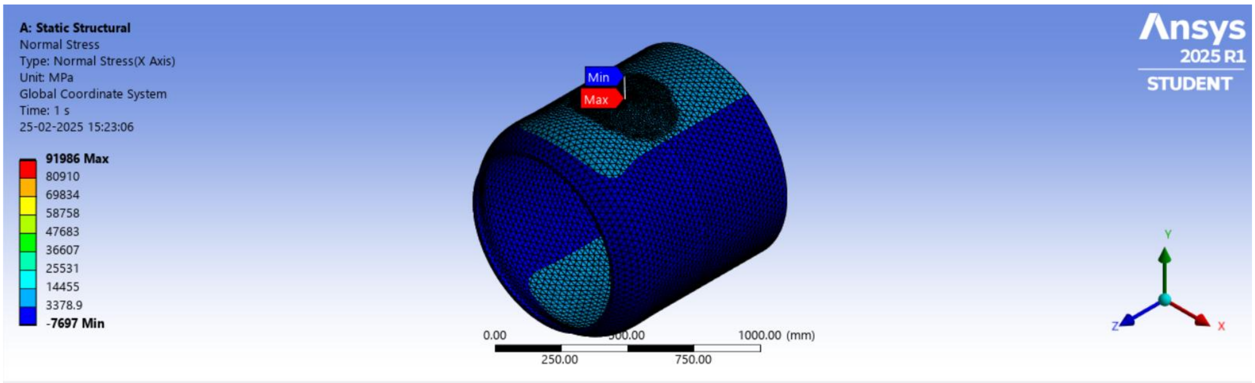
Pressure
Time: 1. s
25-02-2025 15:15:49
Pressure: 200. MPa
Ansys
2025 R1
STUDENT
0.00
500.00
1000.00 (mm)
250.00
750.00

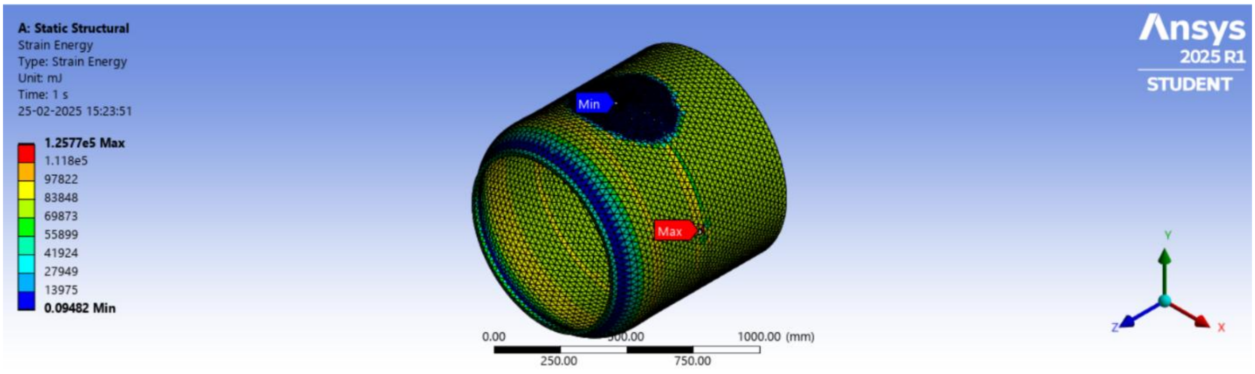

A: Static Structural
Fixed Support
Time: 1. s
25-02-2025 15:16:07
Fixed Support
Pan
Shift the position (up or down and side to side) of the model in the Geometry window.
Press F1 for help.
Ansys
2025 R1
STUDENT
0.00
500.00
1000.00 (mm)
250.00
750.00


A: Static Structural
Force
Time: 1. s
25-02-2025 15:16:27
Force: 450. N
Components: 0.,0.,-450.
Ansys
2025 R1
STUDENT
0.00
500.00
1000.00 (mm)
250.00
750.00


A: Static Structural
Normal Elastic Strain
Type: Normal Elastic Strain(X Axis)
Unit: mm/mm
Global Coordinate System
Time: 1 s
25-02-2025 15:21:49
Automatic
0.27234
0.23106
0.18978
0.1485
0.10722
0.065937
0.024657
-0.016623
-0.057903 Min
Min
Max
Ansys
2025 R1
STUDENT
0.00
1000.00 (mm)
250.00
750.00


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1 s
25-02-2025 15:22:28
10.748 Max
9.554
8.3597
7.1655
5.9712
4.777
3.5827
2.3885
1.1942
0 Min
Max
Min
Ansys
2025 R1
STUDENT
0.00
1000.00 (mm)
250.00
750.00


A: Static Structural
Normal Stress
Type: Normal Stress(X Axis)
Unit: MPa
Global Coordinate System
Time: 1 s
25-02-2025 15:23:06
91986 Max
80910
69834
58758
47683
36607
25531
14455
3378.9
-7697 Min
Min
Max
Ansys
2025 R1
STUDENT
0.00
500.00
1000.00 (mm)
250.00
750.00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Strain Energy
Type: Strain Energy
Unit: mJ
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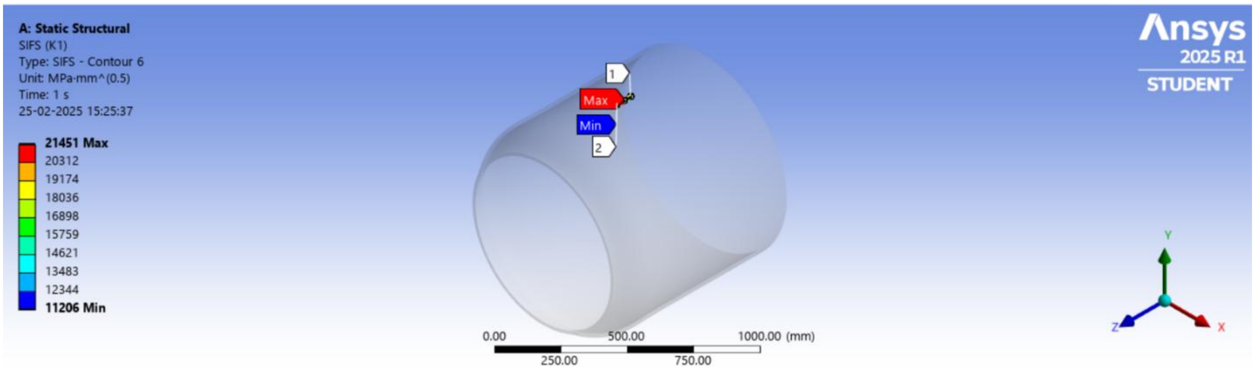
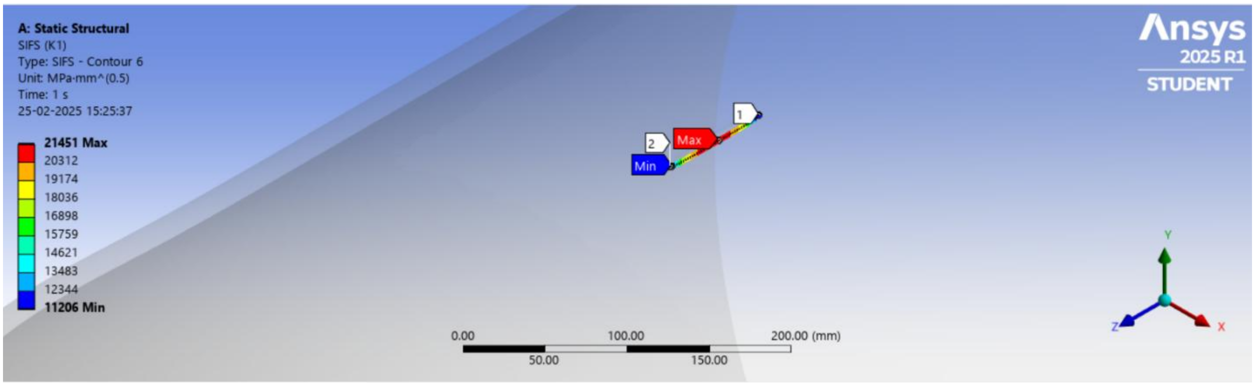
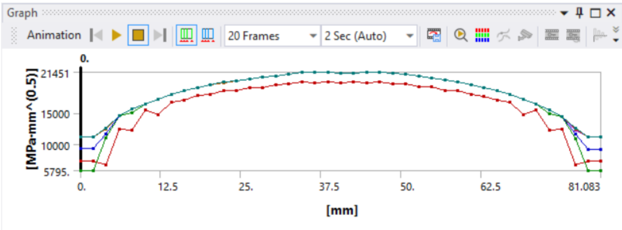
1.2577e5 Max
1.118e5
97822
83848
69873
55899
41924
27949
13975
0.09482 Min
Min
Max
Ansys
2025 R1
STUDENT
0.00
500.00
1000.00 (mm)
250.00
750.00

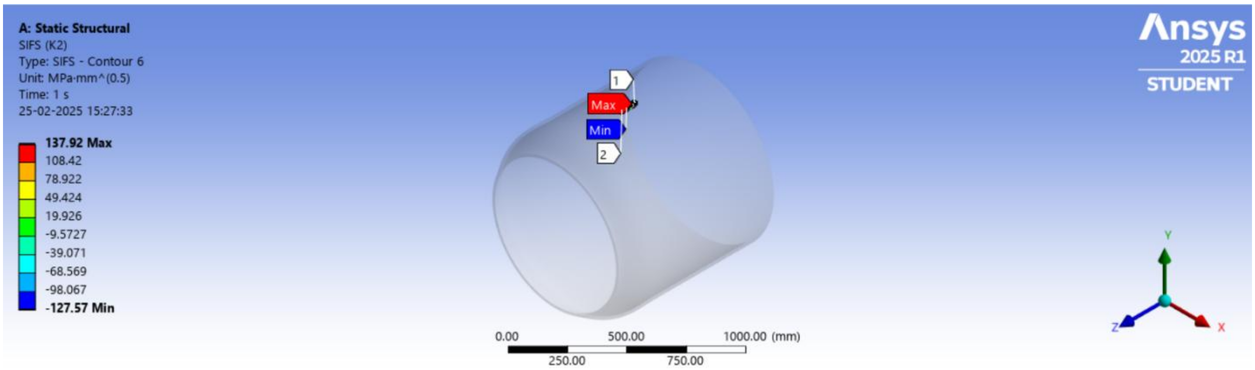

A: Static Structural
SIFS (K1)
Type: SIFS - Contour 6
Unit: MPa·mm^(0.5)
Time: 1 s
25-02-2025 15:25:37
21451 Max
20312
19174
18036
16898
15759
14621
13483
12344
11206 Min
1
Max
Min
2
Ansys
2025 R1
STUDENT
0.00
500.00
1000.00 (mm)
250.00
750.00

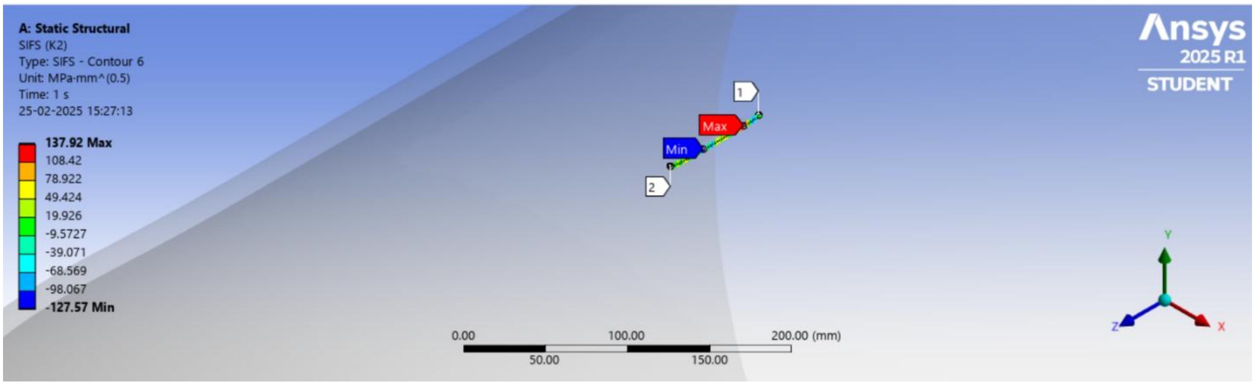

A: Static Structural
SIFS (K1)
Type: SIFS - Contour 6
Unit: MPa·mm^(0.5)
Time: 1 s
25-02-2025 15:25:37
21451 Max
20312
19174
18036
16898
15759
14621
13483
12344
11206 Min
1
2
Max
Min
Ansys
2025 R1
STUDENT
0.00
100.00
200.00 (mm)
50.00
150.00

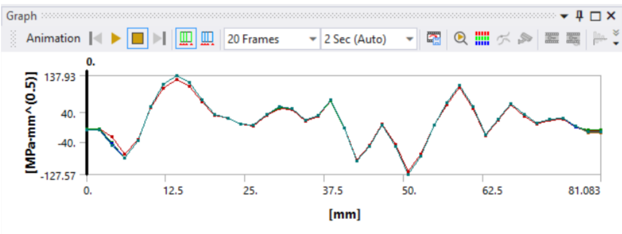


Tabular Data

	Length [mm]	SIFS (K1) Contour 1 [MPa·mm^(0.5)]	SIFS (K1) Contour 2 [MPa·mm^(0.5)]	SIFS (K1) Contour 3
1	0.	7293.2	5810.9	9255.3
2	2.02	7293.2	5810.9	9255.3
3	3.9662	6723.3	10965	11654
4	5.9981	12443	14495	14502
5	8.0299	12223	14963	15550
6	10.062	15416	16420	16426
7	12.094	14711	17209	17222
8	14.126	16760	17945	17952
9	16.158	17020	18540	18548
10	18.19	17782	19046	19053
11	20.222	17883	19470	19478

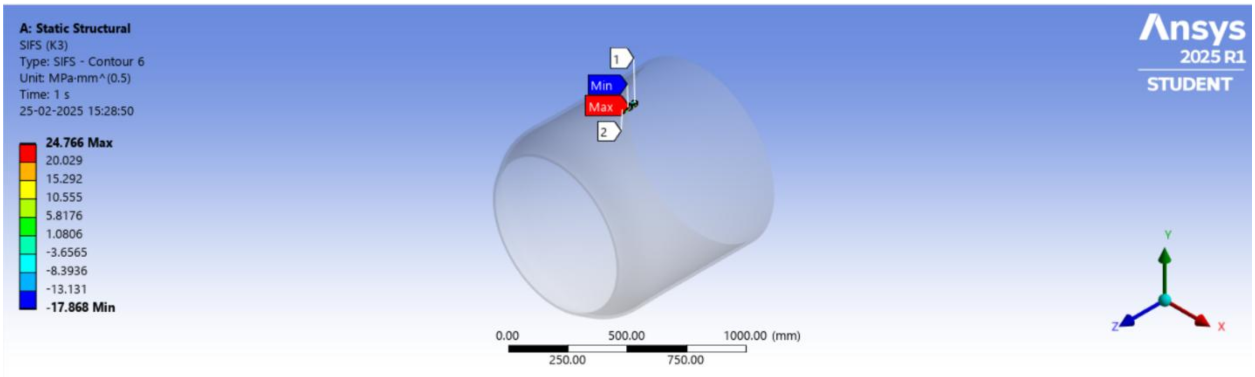


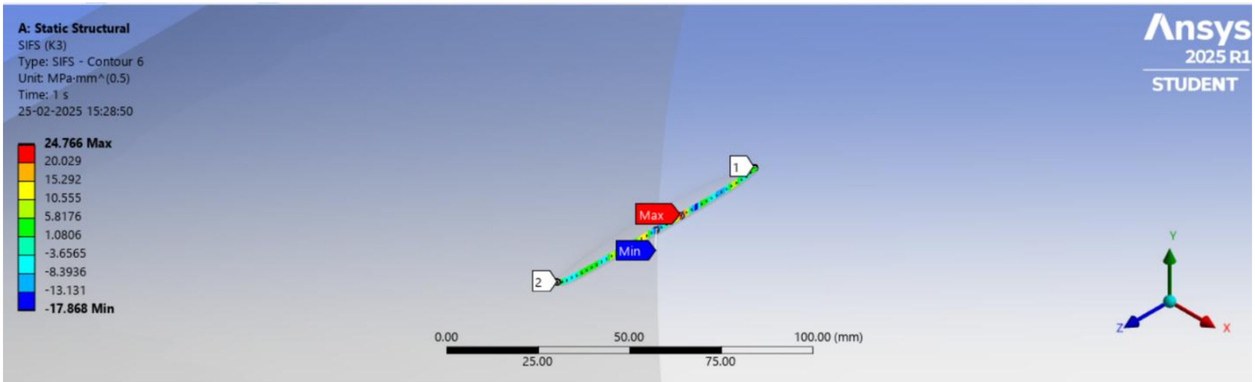


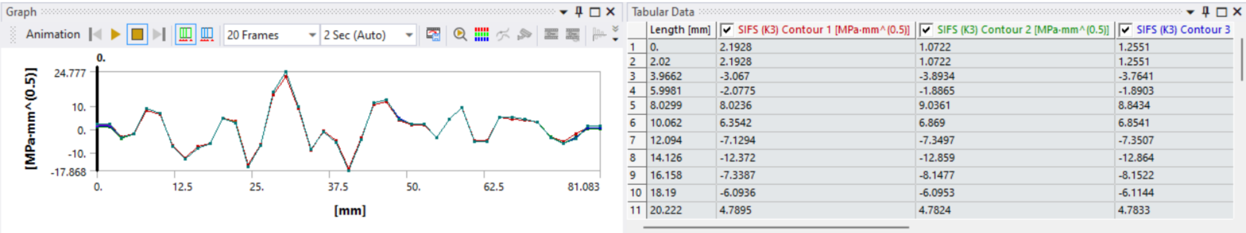


Tabular Data

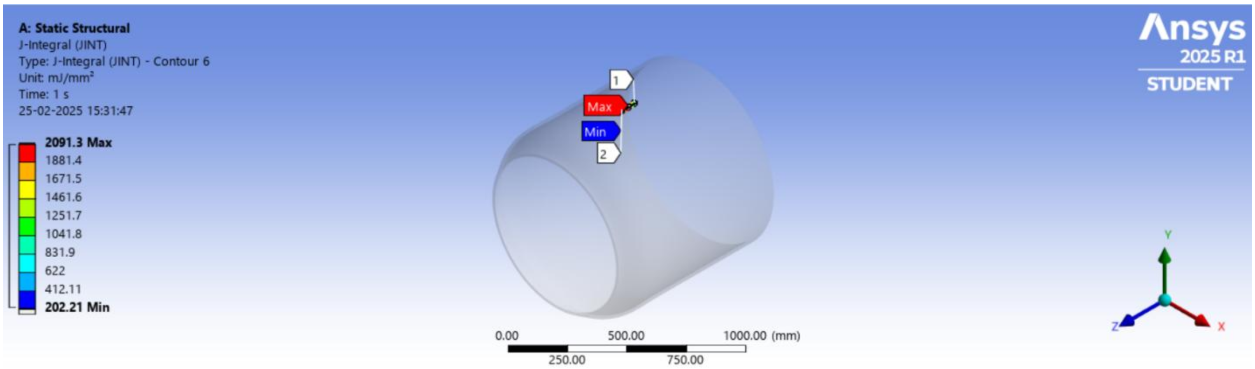
	Length [mm]	SIFS (K2) Contour 1 [MPa·mm^(0.5)]	SIFS (K2) Contour 2 [MPa·mm^(0.5)]	SIFS (K2) Contour 3
1	0.	-5.2143	-4.6089	-7.514
2	2.02	-5.2143	-4.6089	-7.514
3	3.9662	-25.384	-41.194	-44.564
4	5.9981	-72.801	-83.476	-83.565
5	8.0299	-33.525	-35.901	-36.597
6	10.062	51.504	54.76	54.876
7	12.094	103.51	115.71	115.74
8	14.126	127.99	137.93	137.92
9	16.158	108.59	118.43	118.48
10	18.19	68.708	73.351	73.362
11	20.222	30.844	34.095	34.11

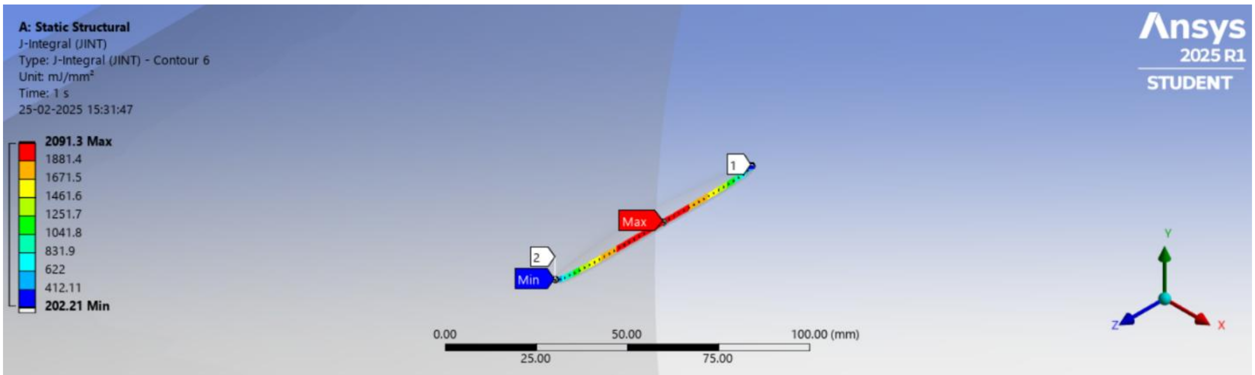


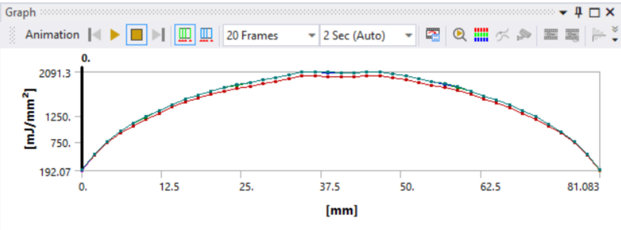


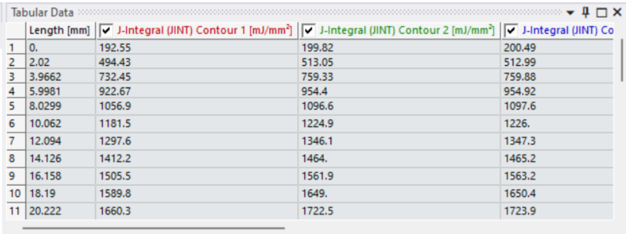


	Length [mm]	SIFS (K3) Contour 1 [MPa·mm^(0.5)]	SIFS (K3) Contour 2 [MPa·mm^(0.5)]	SIFS (K3) Contour 3
1	0.	2.1928	1.0722	1.2551
2	2.02	2.1928	1.0722	1.2551
3	3.9662	-3.067	-3.8934	-3.7641
4	5.9981	-2.0775	-1.8865	-1.8903
5	8.0299	8.0236	9.0361	8.8434
6	10.062	6.3542	6.869	6.8541
7	12.094	-7.1294	-7.3497	-7.3507
8	14.126	-12.372	-12.859	-12.864
9	16.158	-7.3387	-8.1477	-8.1522
10	18.19	-6.0936	-6.0953	-6.1144
11	20.222	4.7895	4.7824	4.7833








Tabular Data

	Length [mm]	J-Integral (JINT) Contour 1 [mJ/mm²]	J-Integral (JINT) Contour 2 [mJ/mm²]	J-Integral (JINT) Co
1	0.	192.55	199.82	200.49
2	2.02	494.43	513.05	512.99
3	3.9662	732.45	759.33	759.88
4	5.9981	922.67	954.4	954.92
5	8.0299	1056.9	1096.6	1097.6
6	10.062	1181.5	1224.9	1226.
7	12.094	1297.6	1346.1	1347.3
8	14.126	1412.2	1464.	1465.2
9	16.158	1505.5	1561.9	1563.2
10	18.19	1589.8	1649.	1650.4
11	20.222	1660.3	1722.5	1723.9

Conclusion

Summary of Findings

The fracture analysis of a hollow cylinder with a semi-elliptical crack was successfully conducted using ANSYS. The stress distribution, crack propagation path, and stress intensity factors were determined, and the results were validated against theoretical predictions.

In this study, the fracture analysis of a hollow cylinder with a semi-elliptical crack was conducted using advanced numerical simulations through ANSYS. The primary objective was to investigate crack growth behavior under different loading conditions, material properties, and geometric configurations. The results obtained provide valuable insights into the mechanisms governing crack initiation, propagation, and the effects of varying factors on the overall structural integrity of the hollow cylinder.

The analysis demonstrated that the stress intensity factor (SIF) plays a crucial role in determining crack propagation, with higher stress values leading to faster crack growth. The location and orientation of the crack were found to significantly influence the crack growth pattern, with cracks propagating more rapidly in regions of higher stress concentration. The study also highlighted the importance of fracture toughness in mitigating the propagation of cracks, especially in materials with higher resistance to crack growth.

By evaluating the critical stress levels and comparing the results with fracture toughness criteria, it was established that the hollow cylinder's failure can be predicted with reasonable accuracy. The results showed that the crack growth in the material could be controlled by adjusting material properties, such as increasing the fracture toughness, or by modifying the loading conditions, such as reducing applied stresses.

Furthermore, the findings emphasize the importance of conducting fracture analysis in the design phase of structural components. It provides engineers with the tools to predict failure and implement preventive measures, such as material selection, design modifications, or maintenance protocols, to extend the lifespan and safety of critical components.

CONCLUSION:

In conclusion, this study underscores the significance of fracture analysis in understanding the behavior of cracked structures and contributes to the broader field of fracture mechanics. Future work could expand on these findings by exploring different crack configurations, materials, and more complex loading scenarios, as well as integrating experimental validation to further refine predictive models and design strate*gies*

Future Work

Future work could involve the analysis of crack growth under cyclic loading and the effect of material anisotropy on fracture behavior.