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Optimize Robotic Arm Design for Fatigue Loading Using ANSYS for Multiple Materials

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Abstract: This study presents a comparative structural analysis of a robotic arm subjected to combined loads and applied moments at one end, while the opposite end remains fixed. The deflection results indicate that minimum displacement occurs at the fixed end (0.0 m), whereas maximum deflection appears at the loaded end, reaching 0.00026 m for the base material. The equivalent stress distribution varies from 7.22 × 10⁵ Pa to 3.075 × 10⁸ Pa, with minimum stress typically occurring at the mid-section and maximum stress near the loaded or constrained regions. Similar mechanical behaviour is observed for ABS polymer, where the deflection ranges from 0 to 0.0137 m, and the equivalent stress varies between 7.24 × 10⁵ Pa and 3.06 × 10⁸ Pa. Titanium also follows the same pattern, showing a minimum deflection of 0 m at the lower end and a maximum of 0.000133 m at the upper end, with equivalent stress ranging from 7.23 × 10⁵ Pa to 3.03 × 10⁸ Pa. Fatigue analysis reveals that the safety factor varies between 0.8125 and 15, reflecting the influence of cyclic loading on arm life. The fatigue life decreases significantly when applied load increases to 150%, whereas a 50% reduction in load enhances the life beyond 10⁵ cycles, approaching theoretical infinite life. Overall, the results demonstrate that increasing arm dimensions or reducing load effectively improves the structural and fatigue performance of the robotic arm across all materials studied.
Keywords: Robot Robotic Arm , Stress in arm , Deflection , Safety factor.

I. INTRODUCTION

A robot is a programmable machine capable of carrying out tasks automatically or semi-automatically with high speed, accuracy, and efficiency. Robots are designed to mimic or extend human actions, often using sensors, actuators, and controllers to interact with their environment. Robotics combines concepts from mechanical engineering, electrical engineering, computer science, and artificial intelligence to develop intelligent machines that can perform tasks ranging from simple repetitive operations to complex decision-making activities. Robots are widely used in industries such as manufacturing, healthcare, defense, space exploration, agriculture, and service sectors. Their applications include welding, assembly, surgery, military operations, packaging, and even domestic tasks.

The key advantages of robots are:

- Accuracy & Precision – Capable of reducing human error.
- Efficiency – Can work continuously without fatigue.
- Safety – Perform dangerous or hazardous tasks.
- Flexibility – Programmable for multiple application

A. Introduction to Robotic Arm

A robotic arm is a type of mechanical device designed to mimic the movements and functions of a human arm. It consists of interconnected links (segments) and joints, which allow it to move in multiple directions and perform various tasks with precision. Controlled by motors, sensors, and computer programs, a robotic arm can be programmed to carry out operations such as picking and placing objects, welding, painting, assembling, and even performing delicate surgical procedures.

The concept of the robotic arm originates from industrial automation, where it was first introduced to increase efficiency and reduce human effort in repetitive and hazardous tasks. Today, robotic arms are widely used in manufacturing, healthcare, space exploration, agriculture, and household applications. Their design often includes components such as actuators for movement, sensors for feedback, and end-effectors (like grippers or tools) that interact with the environment.With advancements in artificial intelligence, machine learning, and control systems, modern robotic arms are becoming more autonomous and capable of handling complex tasks with higher accuracy. They play a vital role in industries where precision, speed, and safety are critical, making them an essential element of modern robotics and automation.

II. LITERATURE SURVEY

Recent research in robotic arm technology shows major progress in design, control, and application across multiple fields. Flexible snake-arm robots enable access to confined spaces using improved cable-driven mechanisms and simplified kinematic models. In marine and underwater applications, robotic systems like ARMROV enhance mobility and cleaning efficiency through dynamic stability analysis. Control improvements include hierarchical controllers, DC–DC converter integration, and differential flatness–based tracking, ensuring smoother and more stable motion.

Lightweight and task-specific robotic arms have been developed using 3D printing, optimized kinematics, and vibration-reducing blending techniques for agricultural and industrial tasks. Collaborative dual-arm robots support complex assembly, disassembly, and coordinated motion planning using AI-based optimization and collision-free trajectory generation.

In medical applications, robotic arms improve surgical precision but require cost–benefit optimization. Safety-oriented systems aid electric power maintenance, while space and nuclear robotics utilize shock-absorbing arms, LIBS, and Raman tools for debris capture and hazardous material identification.

Advanced research also includes multi-arm coordination, BCI-based control, stiffness optimization, and high-performance CoSMo-driven arms for improved payload efficiency. Applications in precision agriculture and underwater manipulation benefit from AI, sensing fusion, and real-time control.

Overall, trends highlight lightweight design, adaptive and intelligent control, multi-arm cooperation, and AI integration, driving more autonomy, precision, and efficiency in robotic arm applications across industries.

B. Research Gap

Insufficient Experimental Validation in Real Environments: Many systems—especially underwater, agricultural, and space robotic arms—are validated primarily through simulations. Full-scale field experiments under real environmental disturbances are still limited

Lack of Unified Multi-Arm Coordination Frameworks: Although dual-arm and multi-arm systems exist, research typically addresses planning, control, or compliance separately. A comprehensive framework that integrates perception, trajectory generation, and cooperative manipulation remains underdeveloped.

Limited Use of AI for Autonomous Decision-Making: AI and learning-based approaches (DMIL, PSO optimization, BCI control) are used in isolation. A fully integrated AI architecture for perception, planning, and fault prediction is not yet well established.

Challenges in Stiffness Optimization and Lightweight Design Trade-Offs: Studies on PDI-based stiffness improvement show progress, but there is insufficient research on balancing high stiffness with ultra-lightweight materials, especially for mobile and space robots.

C. Objectives

To analyze the deflection behavior of the robotic arm under combined loading and applied moments for different materials.

To determine the equivalent stress distribution across the arm and identify regions of minimum and maximum stress

To compare structural performance of different materials (Base Material, ABS Polymer, and Titanium) under identical dimensions and boundary conditions.

To perform fatigue analysis and determine the fatigue life, safety factor, and sensitivity of the arm under varying load conditions (50%–150%).

To establish material suitability for robotic arm applications based on strength, deformation, and fatigue life characteristics.

III. METHODOLOGICAL APPROACH

A. ANSYS primarily uses the Finite Element Method (FEM) and Related Numerical Techniques

Finite Element Method (FEM): Divides the structure into smaller elements to solve for displacements, stresses, and other responses.

- Finite Volume Method (FVM): Used in ANSYS Fluent for solving fluid flow equations.
- Finite Difference Method (FDM): Occasionally applied in transient heat transfer analysis.
- Coupled-Field Analysis: Combines different physics (e.g., thermal-structural coupling).
- Modal and Harmonic Analysis: Used for vibration and frequency response studies.

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B. Geometry

Steps to create or import geometry in ANSYS Workbench:
Open ANSYS Workbench drag the Static Structural or desired analysis system into the Project Schematic.
Double-click "Geometry."
Use DesignModeler or SpaceClaim to create geometry:
Use sketch tools (line, circle, rectangle, spline) to draw 2D profiles.
Apply extrude, revolve, sweep, or blend to make 3D bodies.
Import CAD Geometry: You can import models from Solid-Works, CATIA, AutoCAD, or STEP/IGES formats.
Define Named Selections: Identify faces or edges for boundary condition assignment.
Save and Update Project before proceeding to meshing.

C. Simulation

Steps to perform simulation and obtain results in ANSYS Mechanical:

D. Pre-Processing

Assign Material Properties: Define elastic modulus, Poisson's ratio, density, etc.
Meshing: Generate finite elements (choose mesh size, type—tetrahedral or hexahedral).
Boundary Conditions: Fix supports apply loads, pressures, torques, or thermal inputs.

E. Solution Setup

Choose the analysis type (static, thermal, modal, transient, etc.).
Define solver settings, convergence criteria, and time steps (if transient).

F. Solving

Click Solve to let ANSYS compute the response using numerical solvers.
Monitor residuals, convergence graphs, and solver progress.

G. Post-Processing

View results such as:
Total Deformation
Von Mises Stress
Fatigue Life and Safety Factor

IV. RESULT ANALYSES AND CONCLUSION

It is seen from the fig. that the total deflection of both ends varies because of the effects of applied load and moments at one end minimum deflection shown by blue colour and its value is 0.0 at the fixed end, while at other end it gives maximum deflection at which combined load and Moments are applied and value of deflection is 0.00026m.

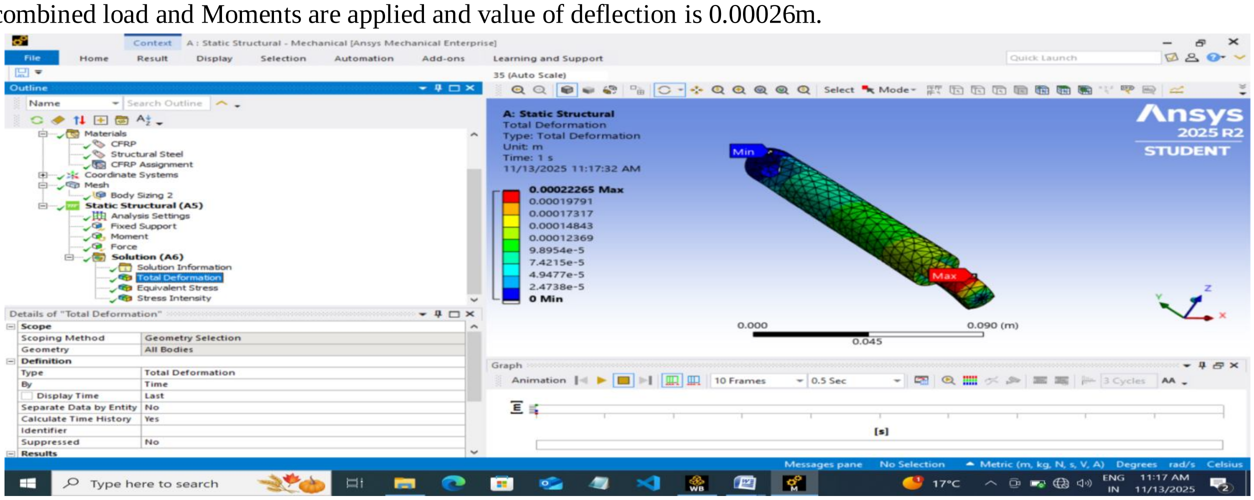

Fig 4.1

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Resulting of applied moments and forces, stress are developed throughout the arm and values of stress are varies from 7.22 X 10 5 Pa to 3.075 X 10 8 Pa blue colour shows the minimum deflection that occurs at the middle portion of the arm , and Maximum deflection occurs other end the value is 3.07 X 10 8 Similarly the stress intensity is shown by the graph it occurs middle portion of the arm while minimum at the lower end where load and moments are applied . And maximum at the other end (fixed end) the minimum and maximum values 8.37 X 10 5 Pa and 3.55 X 10 8 Pa are shown by Blue and red colour.

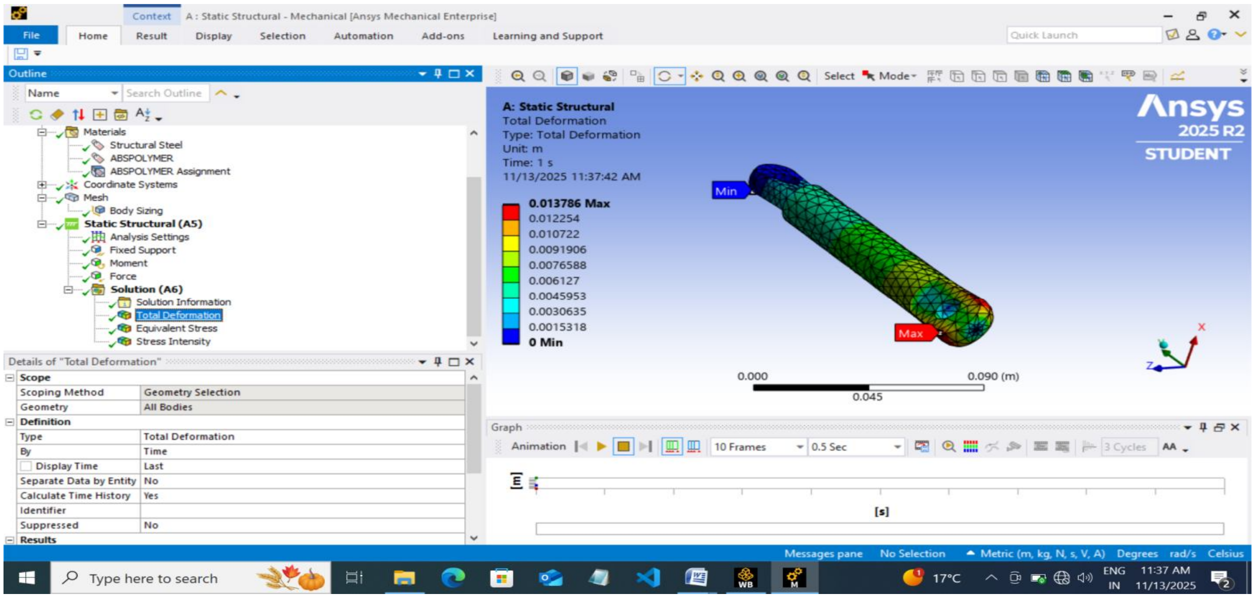


Fig 4.2

Similar result are found for the ABS Polymer Material The minimum deflection is 0 and max deflection is 0.0137m as shown by Blue and red colour. The equivalent stress are shown by the graph, that shows the variation of equivalent stress developed in the arm and values varies from 7.24 X 10 5 Pa to 3.06 X 108 Pa.

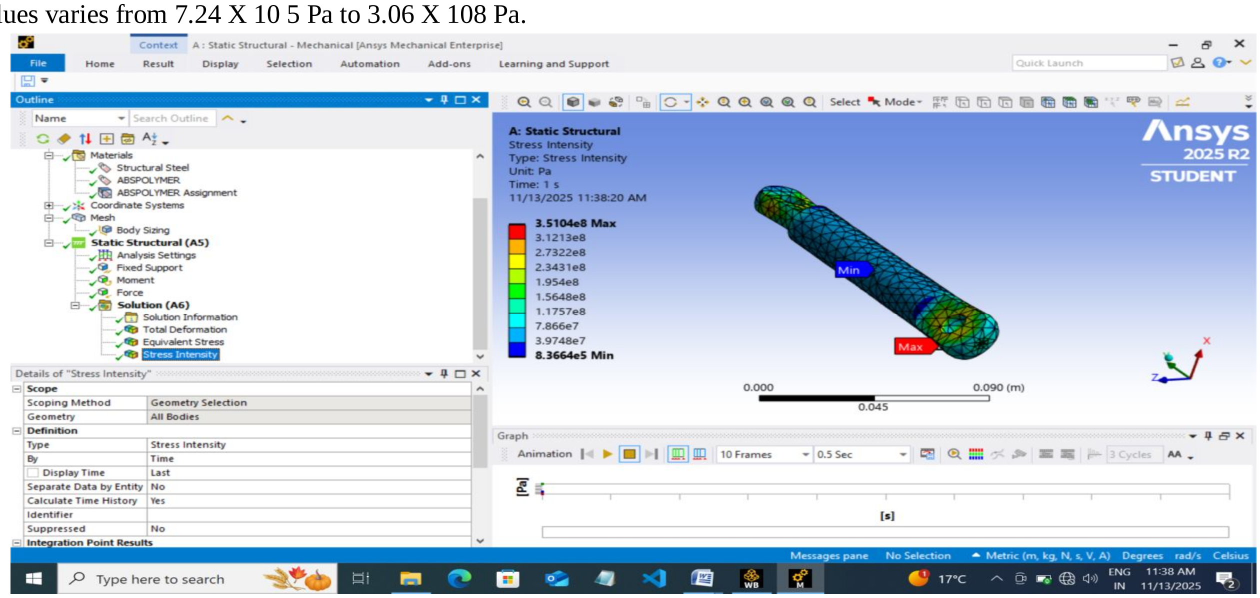


Fig 4.3

The stress intensity is also shown by the graph where values are varies from lower end to upper end 8.35X 10 5 Pa to 3.5 X 10 8 Pa.in the figure blue color shows minimum and Red color shows maximum intensity The titanium material also shows the similar behavior for same dimensional and boundary condition ie applied load and moments that also shows minimum at 0 at lower end and and maximum def at upper end is,0.000133m, similarly equivalent stress are also developed as shown by blue color is, 7.23X105 pa and max. values 3.03X108 Pa shown by red Color, Middle section of the arm is shown by Blue in colour.

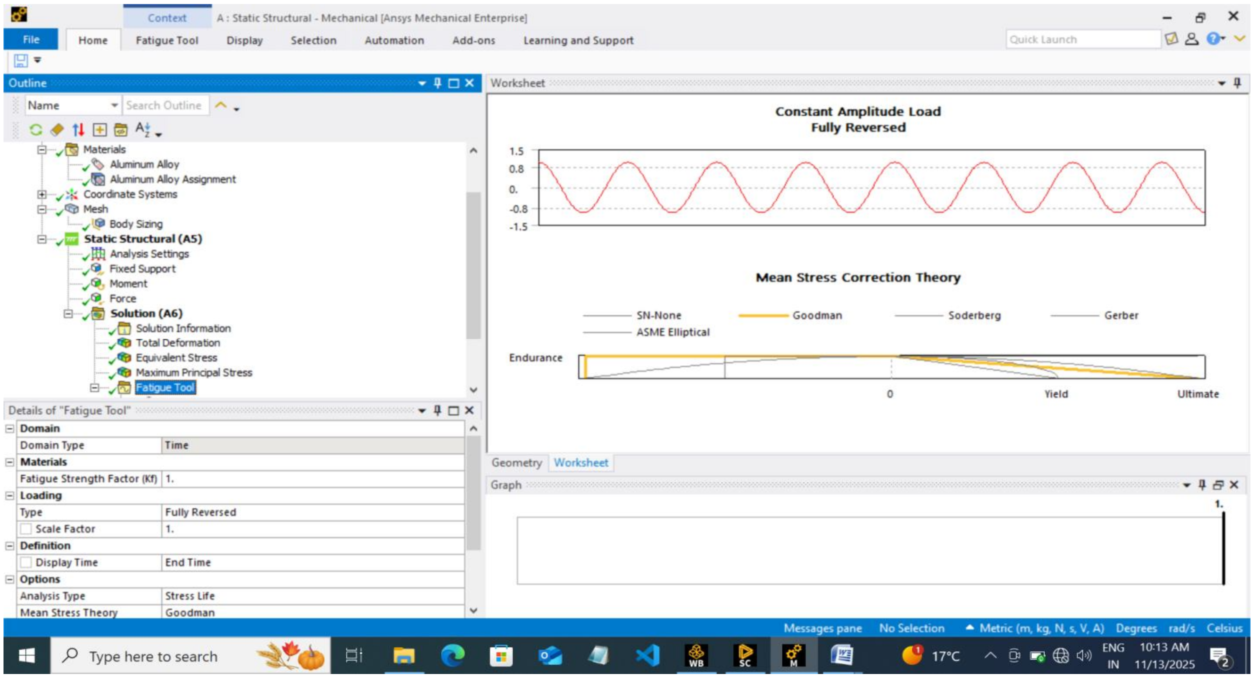


Fig 4.4

The value of safety factor is varies from a minimum value of 0.8125 to max value of 15 , and fig shows how the effect of load is converted into dynamic load and in fatigue load various theories are available for the study life of the robot arm is completely described by the fig red of zero value shows the minimum life of arm and while blue colour shows the maximum life, biaxial stress also shows the dual nature of the load under variable condition.

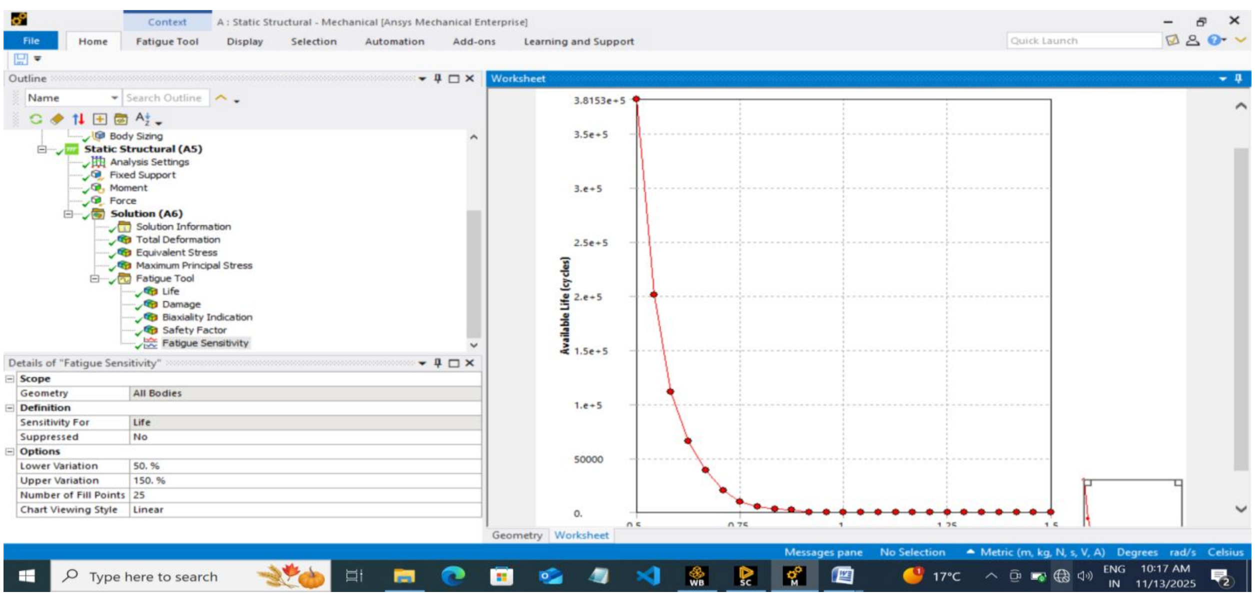
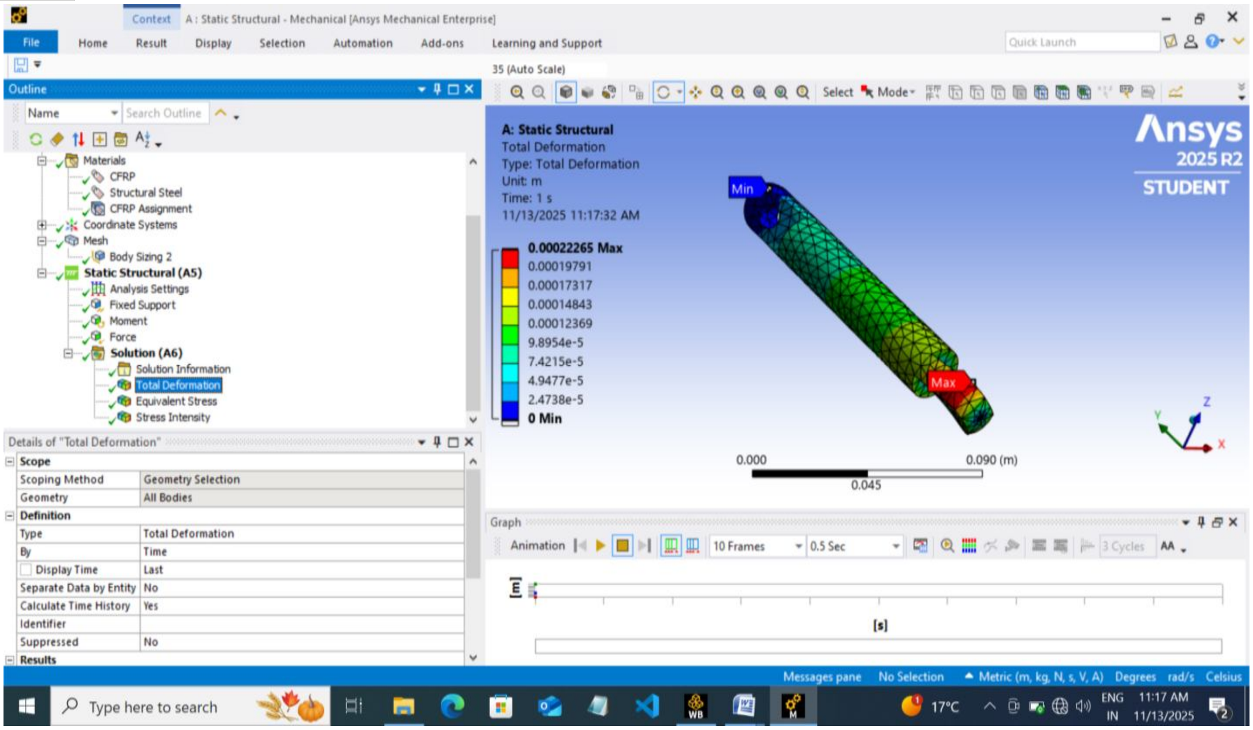


Fig 4.5

Fatigue sensitivity graph it is generated between 50 % to 150 % of the applied load if the load is reduced by 50% The life of arm increases, and increasing load up-to 150% the life of arm is reduced, as described by the fig. 4.5

By reducing the applied load or by increasing the dimension of the Arm , the life of the arm can be increased greater than 10 5 cycle theoretically it is known as infinite life of Arm or any machine



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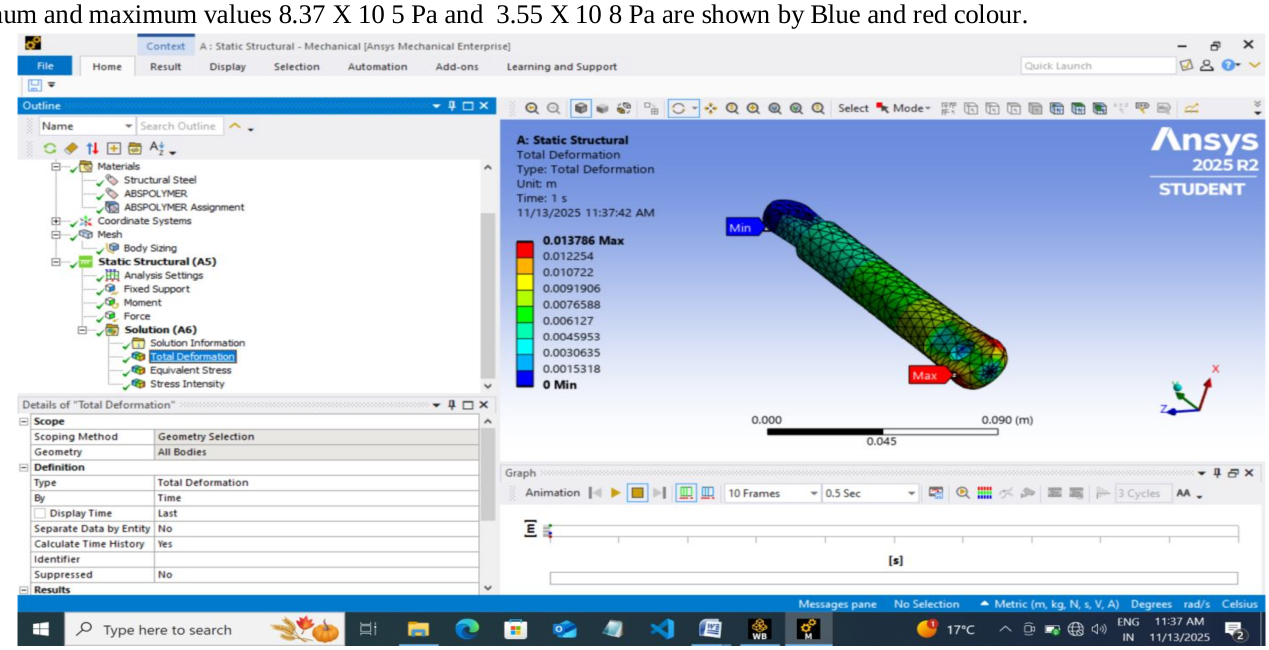

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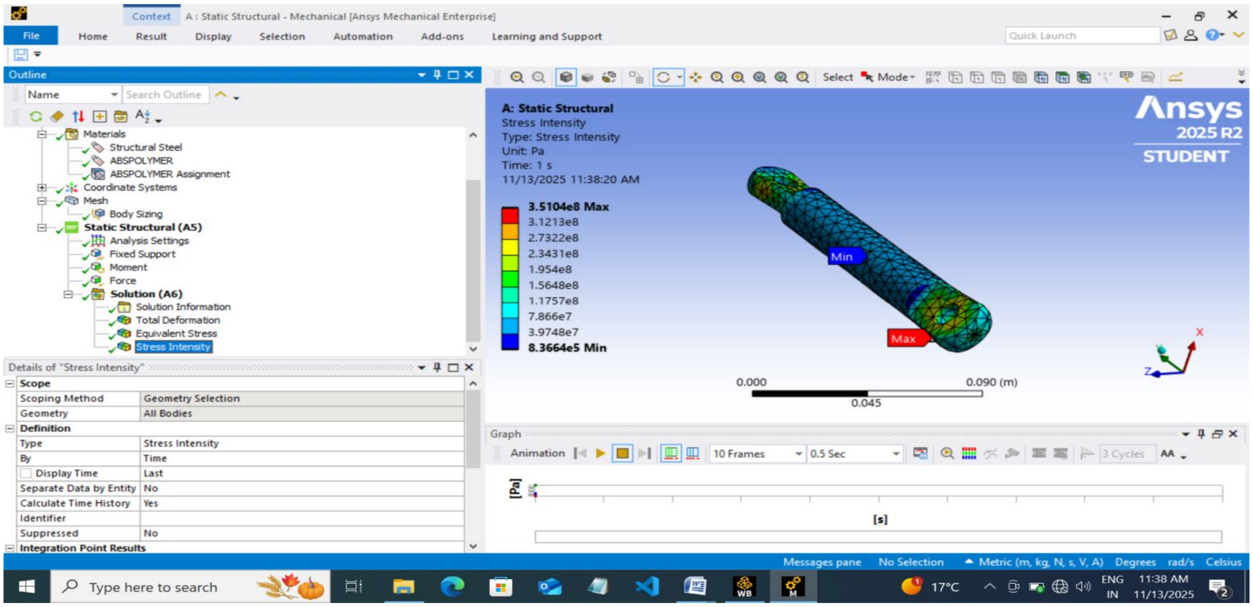

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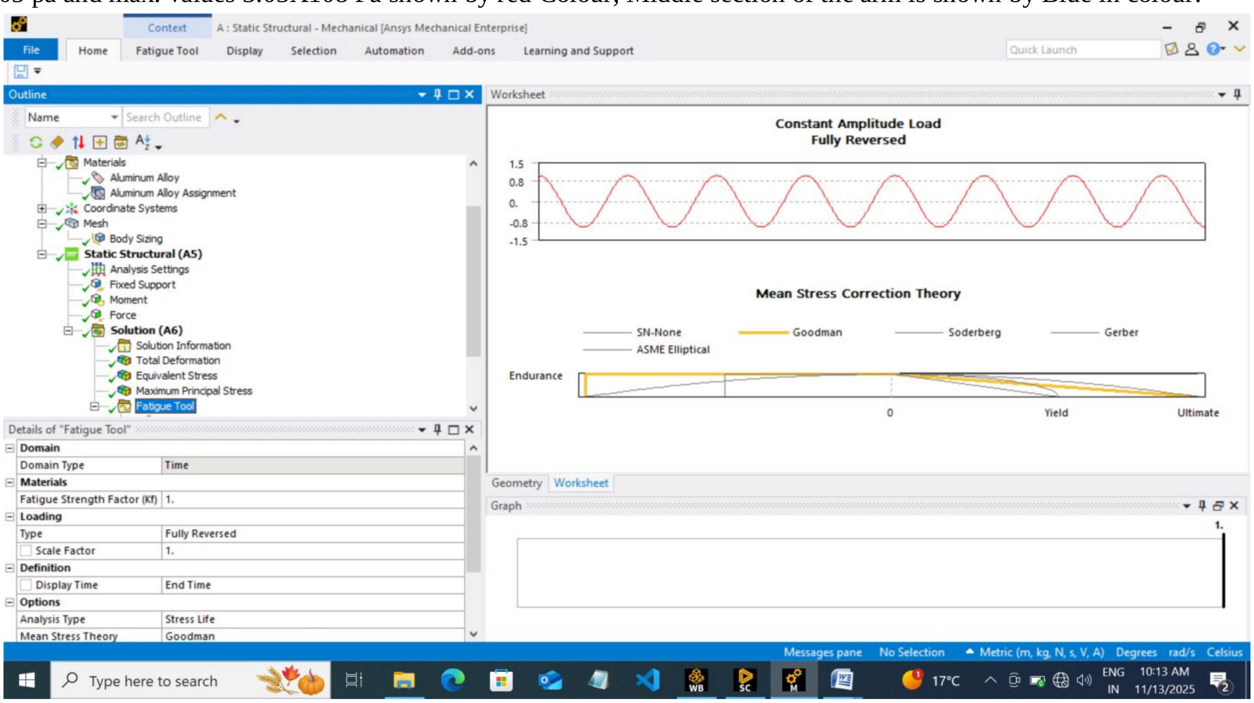

Fig 4.9

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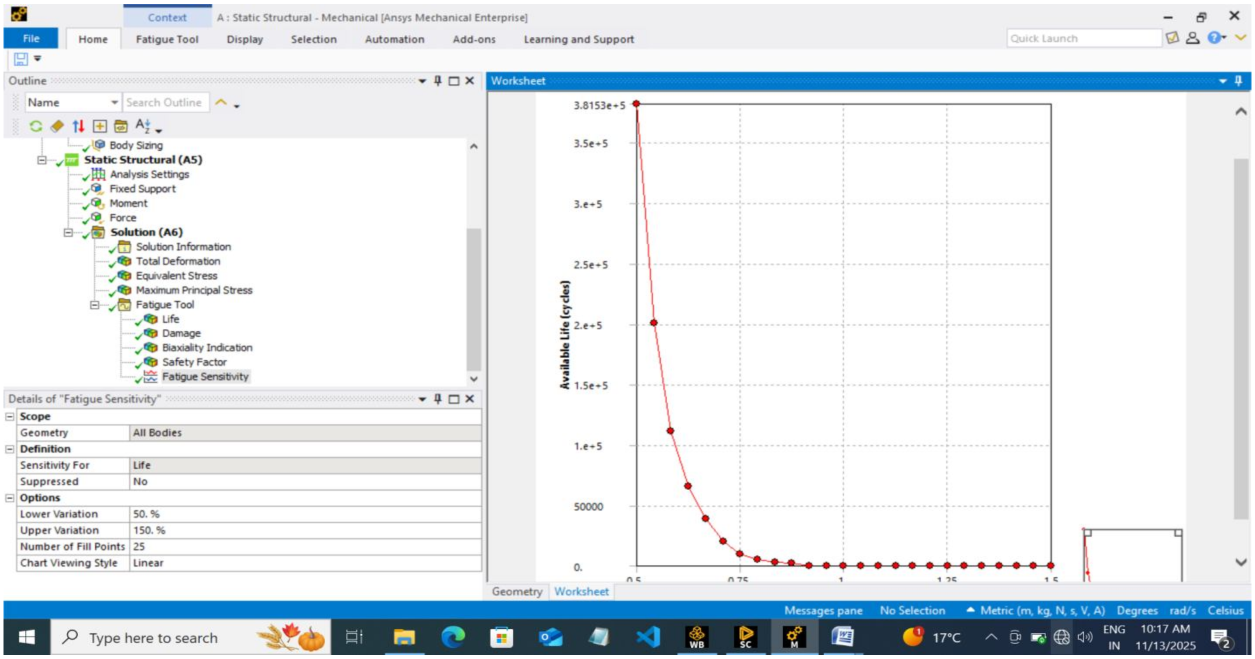

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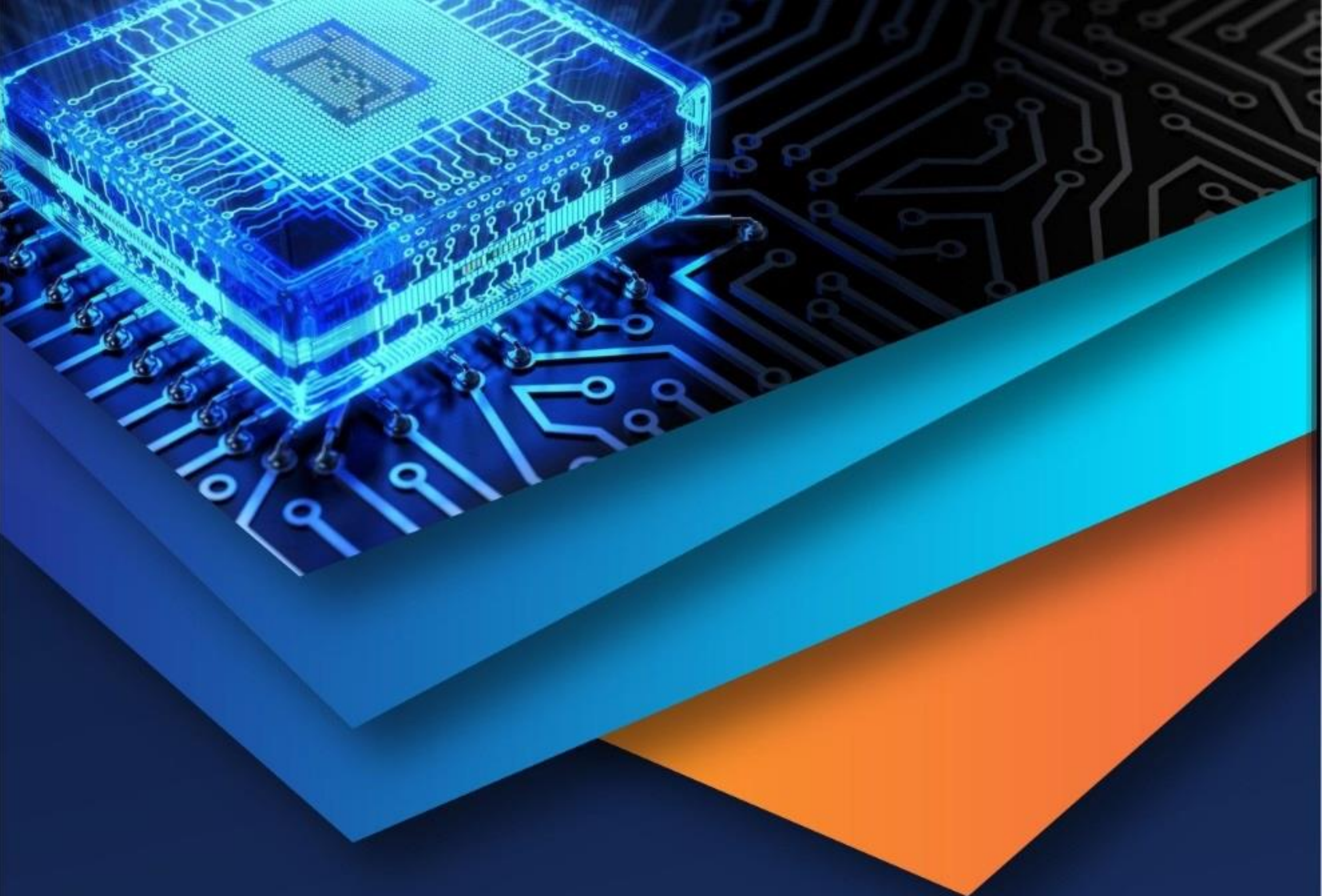

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