# Design And Analysis of a Pipe Inspection Caterpillar Robot Using Different Materials

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**Abstract**

The development of a pipe inspection robot employing caterpillar locomotion and constructed with PLA and ABS materials entails a comprehensive process. Beginning with the delineation of specific requirements, such as size and inspection capabilities, the conceptual design is conceived, outlining the robot's features. The subsequent phase involves meticulous 3D modelling using software like SolidWorks, followed by ANSYS analysis to simulate and optimize the robot's structural integrity, stress distribution, and overall performance. PLA and ABS are chosen as 3D printing materials, with PLA offering ease of printing and biodegradability, while ABS contributes durability and temperature resistance. The prototype is then constructed, incorporating motors, sensors, and the caterpillar locomotion system. ANSYS analysis is employed to assess the robot's behaviour under varying conditions, ensuring robustness and reliability. The iterative process of testing and refining the design leads to the optimization of the robot's performance. The final steps involve thorough documentation, regulatory compliance checks, and potential scalability for diverse applications, culminating in the deployment of the caterpillar robot for effective pipe inspection tasks.

This paper delves into the design and static structural analysis of a caterpillar robot model utilizing ANSYS, with a specific emphasis on assessing two distinct materials: Acrylonitrile Butadiene Styrene (ABS) and Polylactic acid (PLA). The study involves a comprehensive comparison of various parameters between the two materials, aiming to provide insights into their respective performance and suitability for the caterpillar robot's structural components.

**Key Words**: Caterpillar Robot, Solid works, ANSYS, ABS & PLA

## 1. INTRODUCTION

Robotics is one of the fastest growing engineering fields of today. Robots are designed to remove the human factor from labour intensive work. The main concept behind the making of an in-pipe inspection robot is to lower the cost of labour and increase safety and accuracy in inspection. We did design and analysis of robot considering the complexity in pipes used in various power plants. Our robot can adapt itself according to the varying pipe diameter ranging from 170-200mm. The oil, steam and water distribution pipelines as well as heavy industrial plants require routine inspection. We have used single joint locomotive system so that our robot can pass through horizontal and incline pipes. The microcontroller is used for making robot fully autonomous. The Wireless camera is mounted at the front side of the assembly which can cover front area of the pipe. The result of camera is given through the receiver connected to LED screen. The range of camera receiver is approximately 25m while that of the remote is 8m.

Pipelines are used to transport all kinds of fluids, such as toxic, highly flammable fluid and others partially unreactive. In every scenario, it is important that transported fluid is to be contained within the pipeline, under ideal situations. However, every pipe is depended on the material from which it is designed, it deteriorates progressively with time, and the pipe becomes prone to cracks and corrosion. Many accidents have occurred from fluid leaks due to the cracks and corrosion of pipelines. Autonomous pipe inspection method is introduced to improve the efficiency and reduce manpower in the inspection process. One effective way of doing this is to perform regular or periodical inspection of pipelines.

**1.1 Advantages of Pipe Inspection Robot:**

Man cannot enter in the small pipes for inspection so this system used there.

- To avoid leakage of crude or water from pipeline.
- Maintenance cost low.
- Easy to operate.
- Inspect borewell pipe lines

## 2. LITERATURE REVIEW

In this literature study, research was conducted to comprehend the mechanisms of various types of in-pipe robots. Additionally, literature work was undertaken on various sensors employed for inspecting the in-pipe environment to detect flaws in pipelines, which serve as a crucial means for long-distance transport of materials like oil, gas, water, and solid capsules, among others. In various industries, pipelines play a vital role in fluid transport, and in urban areas, they are essential for carrying sewage water. Any defects in pipelines can lead to losses or pose hazards to the surrounding areas.

Oluwafemi Ayodeji Olugboji et al. [1] designed and developed an intelligent pipe inspection gauge to check the impulses experienced by the gauge as it traveled inside the pipe. Impulses were detected by analyzing vibrations during its movement along the pipe. Devesh Mishra et al. [2] studied and designed a model for pipeline inspection and maintenance, capable of measuring diameter, inspecting corrosion, deformation, detecting leakage, and identifying the build-up of scale. They also explored kinematic analysis, pigging phenomena, and the hall effect. Giancarlo Bernasconi et al. [3] investigated pipe inspection gauge tracking and positioning to achieve optimal inspection. They focused on three techniques to capture noise generated by the Pipeline Inspection Gauge (PIG) during operation, as researched by Sangdeok Park et al. [4]. This system moved from the outside but detected internal defects such as pinholes and cracks. Two robotic systems were developed for inspecting boiler tubes to identify reductions in pipe walls above 1mm.Toshihiro Yukawa et al. [5] described a magnetic wheel used for inspecting pipelines made of ferromagnetic material. They examined the mechanism of the robot, deriving kinematics and adhesion conditions based on horizontal piping. Vladimir Kindl et al. [6] addressed the redesign of the wheel, aiming to increase attraction force and reduce the overall mass of the wheel. They utilized finite element analysis and a nonlinear finite element approach for the design. Myounggyu Noh et al. [7] derived analytical force by calculating the reluctance force between mating surfaces, and the model was validated through finite element analysis and a test rig. Minghui Wu et al. [8] focused on adhesion force and the mechanism for passing over obstacles for a wheel robot. The mechanism included lifting the body of the robot to avoid obstacles by varying adhesive forces.Zhongcheng Gui et al. [9] developed a robot for welding with colossal load-carrying capacity and high adsorption reliability. They showcased an inchworm mechanism with two switchable magnets for adhesion. Peidro A. et al. [10] presented the design and implementation of magnetic grippers for exploring ferromagnetic structures using two designing approaches: Zero-point moment and static friction analysis. They also studied failure modes, including detaching and slippage. Andrew Garcia et al. [11] researched switchable magnets to investigate power efficiency. Naoto Imago et al. [12] fabricated a Hermit crab model with spokeless wheels made of magnets. Xu Fengyu et al. [13] designed a model to check for internal steel cracks and cylindrical cables and poles defects, focusing on obstacle avoidance and climbing principles and analyzing the dynamic characteristics of the model. Ram Sudhir et al. [14] developed a pole climbing model using a spring mechanism to climb up and down on poles. Toshio Fukuda et al. [15] developed a model for a 90mm diameter pipe with arms, a hook, and a tensioner, utilizing a spring arrangement. F. Javier Garcia Rubiales et al. [16] developed a gripper mechanism for unmanned aerial vehicles inspecting pipes. They used additive techniques for the mechanism and conducted various tests to ensure grasping capacity. P. Ramon-Soria et al. [17] developed a gripping mechanism for aerial systems, focusing on improving the grippers used. They replaced earlier models that required precise positioning and a larger contact area with soft tendon actuators, providing firm gripping. Radhen Patel et al. [18] demonstrated improvements in grasping ability using tactile sensors and proximity sensors. They studied various gripping phases, including approach, alignment, contact, lift, slip, disturbance, placement, and release. Hidemi

Hosokai et al. [19] designed and implemented a lazy tongs mechanism to climb pipes of various diameters and detect reducers and diffusers. They studied an algorithm for motion control for the robot to pass over reducers. Varshil .H Patel [20] conducted a study on the original robot architecture for in-pipe inspection. The robot consisted of two parts articulated with a universal joint. One part was guided along the pipe by a set of wheels moving parallel to the axis of the pipe, while the other part followed a helical motion thanks to tilted wheels rotating about the axis of the pipe. A single motor was placed between the two bodies to produce the motion. All the wheels were mounted on a suspension to accommodate changing tube diameter and curves in the pipe.

## 3. METHODOLOGY

The inspection of iron and steel pipes within industrial settings is of paramount importance for ensuring the continued safe and reliable operation of infrastructure. Pipelines constitute a critical component of various industries, including energy, transportation, and manufacturing. However, the inspection of these pipelines presents a significant challenge due to the often harsh and inaccessible environments in which they are situated. Traditional inspection methods, such as manual inspection and stationary monitoring, have their limitations in terms of accessibility, efficiency, and accuracy, leaving room for innovation and technological advancement.

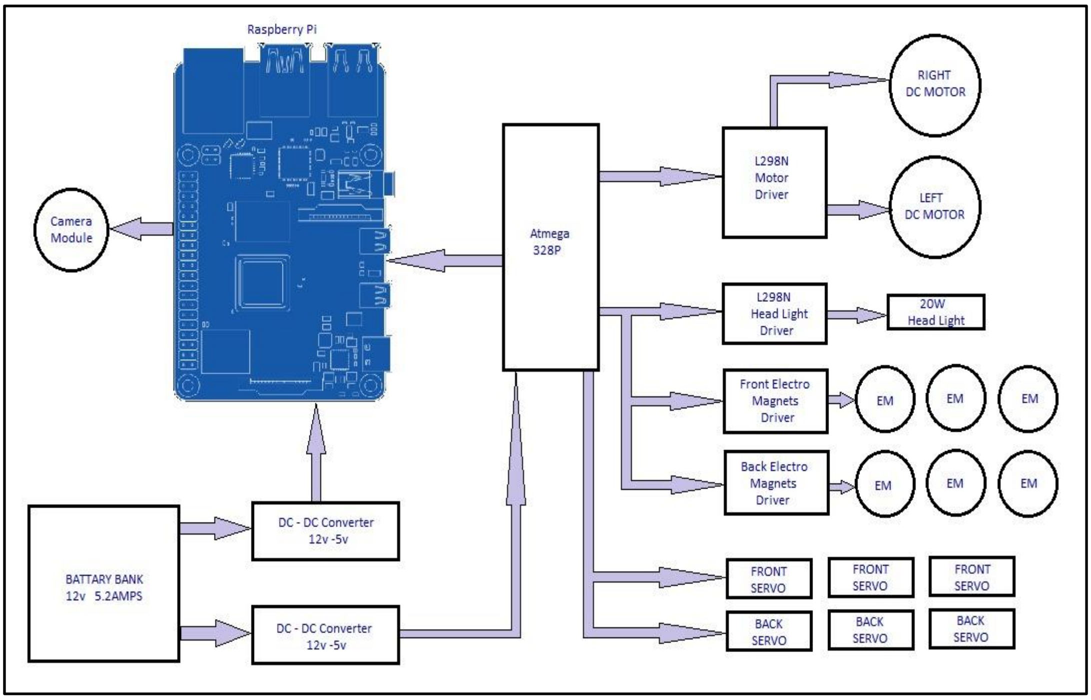


**Figure 3.1: Block Diagram of The Model**

This autonomous robot utilizes image processing to identify cracks and rust within pipes, employing a Raspberry Pi with an onboard camera, controlled by an Arduino Pro Micro. The robot features two sets of three electromagnets at the front and rear, providing a secure grip on the pipe's inner surface, driven by a current amplifier driver. Its locomotion is powered by two geared DC motors, managed by the L298N Driver board, connected to linear actuators with a ball screw mechanism. The robot hovers and moves forward by expanding the linear actuators with CW rotation of the motors while activating servo motors attached to front electromagnets. The Arduino triggers the Raspberry Pi at GPIO 4 for image capture and analysis, with the aid of 20W headlights for clear images. The robot calculates the distance traveled based on the number of commands received, with each hover cycle covering 10 cm. A 5.2 Amps/hr Li-Po 12V battery powers the robot, with DC-to-DC converters adapting the voltage for the Raspberry Pi and Arduino. An HCSR-04 ultrasonic distance sensor aids in detecting junctions and obstacles, enabling turning manoeuvres when needed. Once the autonomous pipe inspection is complete, the Raspberry Pi can connect to a TV or monitor via an onboard HDMI port, or images can be accessed through a connected pen drive.

**3.1 : 3-D Printing of the Robot Experimental Model**

The Robot model was printed on "CREALITY CR 10 Smart 3D Printer". The Creality CR-10 Smart 3D Printer is an advanced and versatile 3D printing device designed to cater to the needs of both hobbyists and professionals. It features a large build volume, which is ideal for creating sizable 3D prints with dimensions of up to 300 x 300 x 400mm. The printer incorporates a range of innovative features, including Wi-Fi connectivity for remote printing and monitoring, a robust direct drive extruder for precise filament control, and a silent motherboard to minimize operational noise. Its touchscreen interface offers user-friendly navigation, while auto-levelling ensures accurate prints. The CR-10 Smart is compatible with various filament types, including PLA, ABS, and TPU, providing flexibility in material choices. This 3D printer offers an accessible entry point into the world of 3D printing while providing the capabilities required for more demanding and intricate projects, making it a popular choice for a wide range of users.

**Table 3.1: Specification of CREALITY CR 10 Smart 3D Printer**

| | |
|---|---|
| Printing Size | 300*300*400mm |
| Molding Tech | FDM |
| Nozzle Number | 1 |
| Slice Thickness | 0.1mm-0.4mm |
| Nozzle Diameter | Standard 0.4mm |
| Precision Filament | ±0.1mm |
| Filament | 1.75mm PLA/ABS/TPU/PETG |
| File Format | STL/OBJ/AMF |
| File Transfer | Wi-Fi/storage card |
| Slice Software | Creality Slicer/Cura/Repetier-Host/Simplify3D |
| Power Supply | Input: AC100-240V 50/60Hz Output: DC 24V |
| Total Power | 350W |
| Bed Temp | ≤100℃ |
| Nozzle Temp | ≤260℃ |
| Resume Printing | Yes |
| Filament Detector | Yes |
| Dual Z-axis | Yes |
| Auto Levelling | Yes |
| Printing Speed | 80-100mm/s |

**Figure 3.2: Creality Cr 10 Smart 3D Printer**

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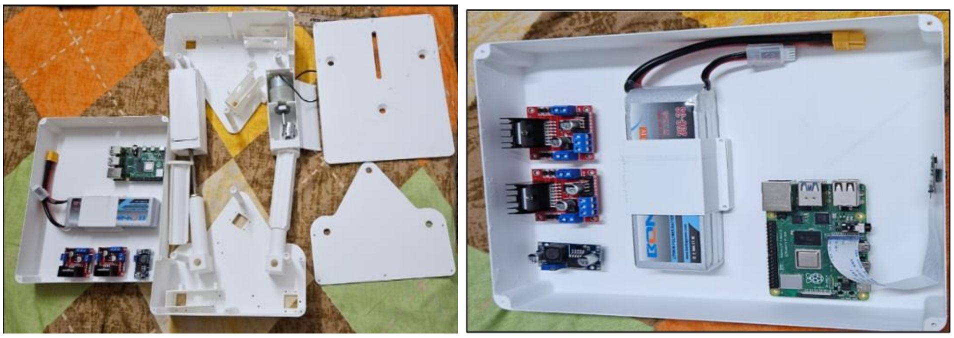

**Figure 3.3: 3-D Printed Components**

The caterpillar robot's chassis and body are crafted from Polylactic Acid (PLA), a favoured 3D printing material, chosen for its eco-friendliness derived from sources like corn starch. PLA's adaptability in 3D printing allows engineers to create intricate custom designs crucial for the robot's functionality, despite its lightweight nature. It possesses sufficient mechanical strength to support the robot's components and withstand typical operational stresses, owing to its biodegradability and eco-friendly properties.

**Figure 3.4: 3-D Printed Legs After Assembly**

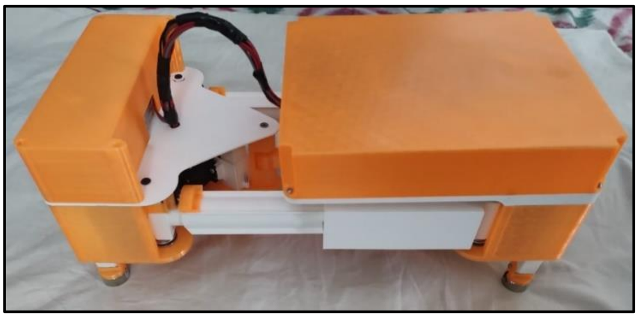

**Figure 3.5: Final 3-D Printed Assembled Model**

**3.2 Various other robotic Pipe Inspection technologies.**

The robotic inspection technologies will help provide context for this technical paper on caterpillar robots for iron and steel pipe inline inspection. Here are some of the notable robotic inspection technologies and the existing research and developments in the field:

**Pipeline Inspection Gauges (PIGs):**

PIGs are autonomous devices that travel through pipelines for inspection and maintenance They are equipped with various sensors, such as magnetic flux leakage (MFL) or ultrasonic sensors to detect defects, corrosion, and other anomalies. PIGs have been widely used in the oil and gas industry for many years. Research focuses on improving sensor technology, navigation, and data analysis.

**Autonomous Underwater Vehicles (AUVs):**
AUVs are used for inspecting underwater pipelines, such as those in offshore oil and gas facilities. They can carry cameras, sonar systems, and other sensors to assess the condition of subsea pipes. Research in this area aims to enhance AUV autonomy, extend operational depth, and improve data quality.
**Unmanned Aerial Vehicles (UAVs):**
UAVs, or drones, have been used for inspecting above-ground pipelines such as those in the energy and utility sectors. They can capture visual and thermal images, as well as use LiDAR or other sensors to identify issues like corrosion, leaks, or vegetation encroachment. Research is ongoing to develop more advanced inspection capabilities and autonomous navigation for UAVs.

### 3.3 CAD Modelling using SolidWorks-2020

The SolidWorks 2020 was allowed for the creation of detailed and precise 3D models and assemblies, facilitating product design and engineering processes with accuracy and efficiency. The following were the SOLIDWORKS CAD models of various components, subassemblies, and final Assembled model.

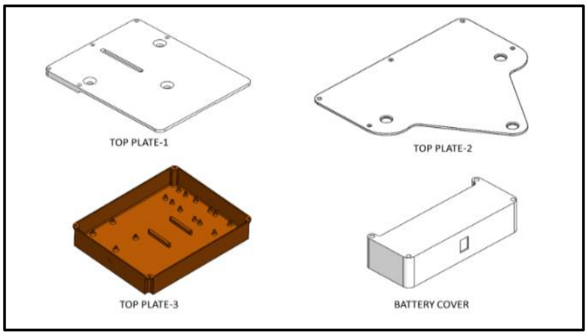


**Figure 3.6: CAD Models of Top Cover Components**

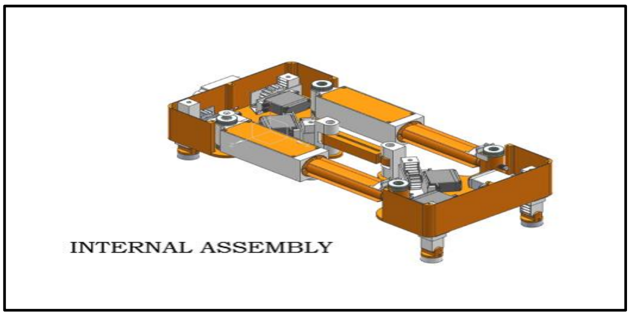


**Figure 3.7: Internal View of Total Assembly**

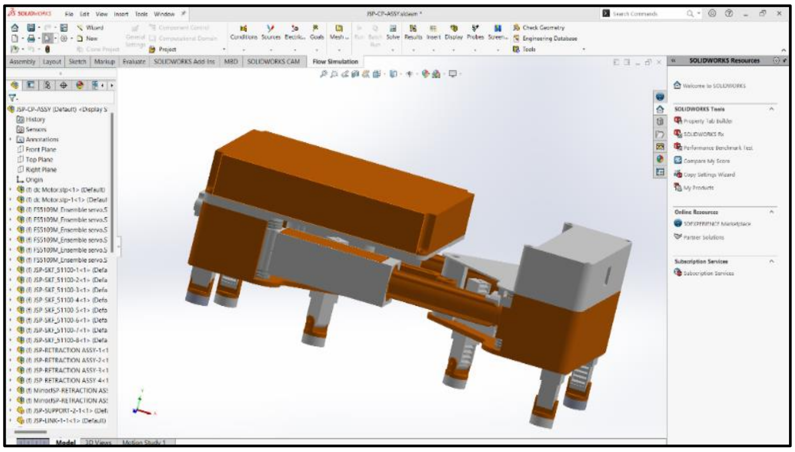


**Figure 3.8: Catter Piller Robot Isometric view**

**3.4 Materials Used**

1. **Acrylonitrile Butadiene Styrene (ABS)**
2. **Polylactic Acid (PLA)**

**Acrylonitrile Butadiene Styrene (ABS) Polymer:**

Acrylonitrile-butadiene-styrene (ABS) polymers are a versatile family of easily processable resins used to create products with excellent toughness, dimensional stability, and chemical resistance. Transparency, unique coloration effects, higher heat performance, and flame retardancy are all available as special product features.

**Properties of ABS:**

When compared to other common polymers, ABS has superior mechanical properties such as impact resistance, toughness, and rigidity to improve impact resistance, toughness, and heat resistance, a variety of modifications can be made.

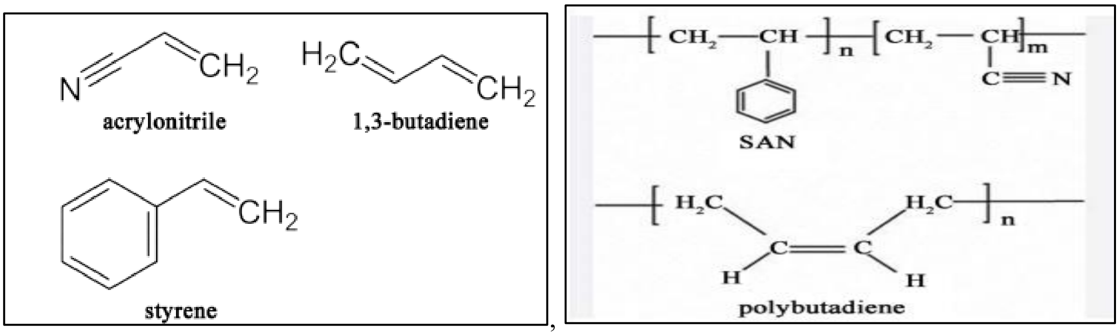


**Figure 3.9: a) Monomer units of ABS, b) Phases of ABS**

**Polylactic acid (PLA):**

Polylactic acid, also known as poly (lactic acid) or polylactide (PLA), is a thermoplastic polyester with backbone formula n or [–C (CH 3) HC(=O) O–] The material properties of PLA make it suitable for the manufacture of plastic film, bottles and biodegradable medical devices, including screws, pins, plates and rods that are designed to biodegrade within 6 to 12 months). PLA can be used as a shrink-wrap material since it constricts under heat.

**Table 3.2: ABS Material properties**

Properties of Outline Row 3: ABS

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit | | |
| 2 | Material Field Variables | Table | | | |
| 3 | Density | 1.05 | g cm^-3 | | |
| 4 | Melting Temperature | 105 | C | | |
| 5 | Isotropic Elasticity | | | | |
| 6 | Derive from | Young's Modulus and Poisson... | | | |
| 7 | Young's Modulus | 2.5 | MPa | | |
| 8 | Poisson's Ratio | 0.38 | | | |
| 9 | Bulk Modulus | 3.4722E+06 | Pa | | |
| 10 | Shear Modulus | 9.058E+05 | Pa | | |
| 11 | Tensile Yield Strength | 43.8 | MPa | | |
| 12 | Compressive Yield Strength | 2E-05 | MPa | | |
| 13 | Tensile Ultimate Strength | 40 | MPa | | |
| 14 | Compressive Ultimate Strength | 65.02 | MPa | | |

**Table 3.3: PLA Material properties**

Properties of Outline Row 4: PLA

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit | | |
| 2 | Material Field Variables | Table | | | |
| 3 | Density | 1.25 | g cm^-3 | | |
| 4 | Melting Temperature | 135 | C | | |
| 5 | Isotropic Elasticity | | | | |
| 6 | Derive from | Young's Modulus and Poisson... | | | |
| 7 | Young's Modulus | 3600 | MPa | | |
| 8 | Poisson's Ratio | 0.38 | | | |
| 9 | Bulk Modulus | 5E+09 | Pa | | |
| 10 | Shear Modulus | 1.3043E+09 | Pa | | |
| 11 | Tensile Yield Strength | 62.63 | MPa | | |
| 12 | Compressive Yield Strength | 66.78 | MPa | | |
| 13 | Tensile Ultimate Strength | 35.6 | MPa | | |
| 14 | Compressive Ultimate Strength | 39.9 | MPa | | |

## 4 SIMULATION APPROCH

In this section to discuss the static structural analysis of Catter Piller Robot to determines the effect of steady (or static) loading on a structure. Stress, strain, and deformation of a structure can be studied under a range of loading conditions.

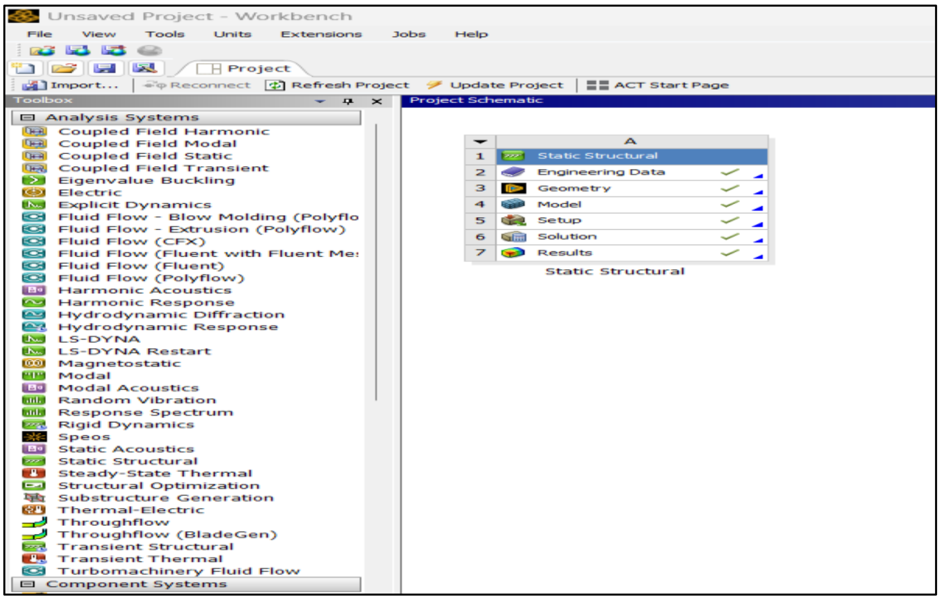


**Figure 4.1: Static Structural ANSYS Layout**

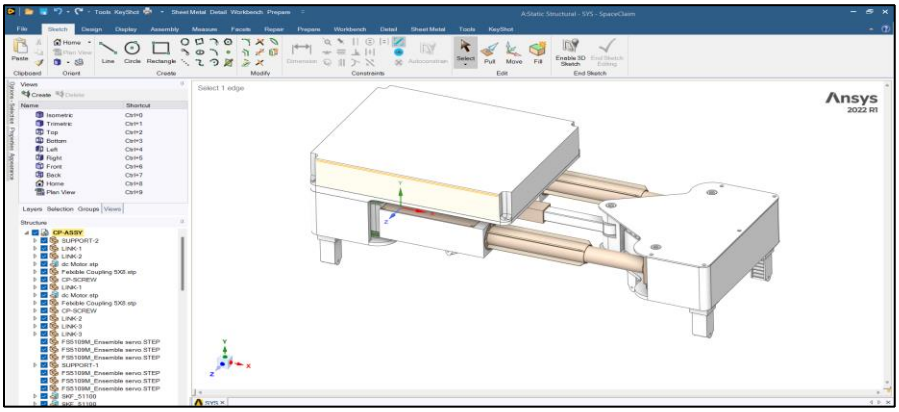


**Figure 4.2: Spacecliam Structure**

**4.1 Static Structural Analysis**

The static structural analysis employed ANSYS to compare the performance of 3D-printed models using ABS and PLA materials. Finite element models, representing identical geometries with distinct material properties, were subjected to equivalent loading conditions. ANSYS accurately calculated stress distributions, deformations, and other relevant factors, enabling a comprehensive comparison of ABS and PLA structural responses. Variations in stress levels, deflections, and failure points were identified, offering crucial insights for material selection in engineering prototypes where structural integrity is paramount. This information played a pivotal role in informed decision-making, considering factors such as strength, cost, and specific project requirements. The triangular face was chosen for force application due to its lack of constraints on one side, adherence to thickness criteria, and relevance to real-world scenarios where visible wear often occurs at surface corners.

**4.2 Static structural Analysis caterpillar Robot using PLA Material**

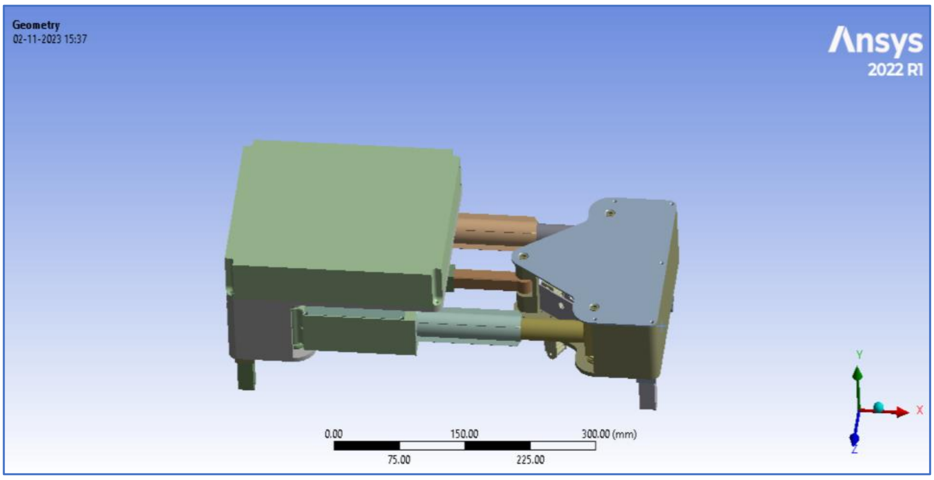


**Figure 4.3: Imported Model**

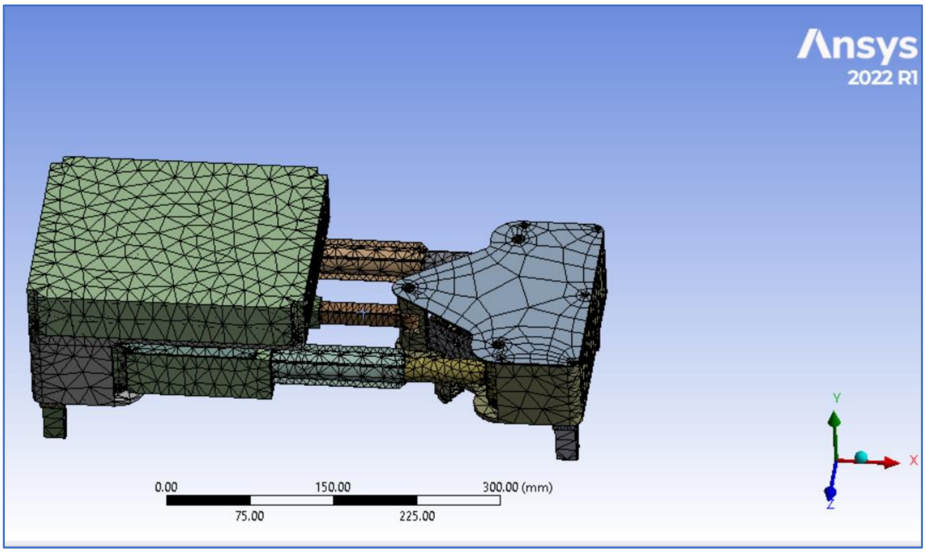


**Figure 4.4: Meshed Model**

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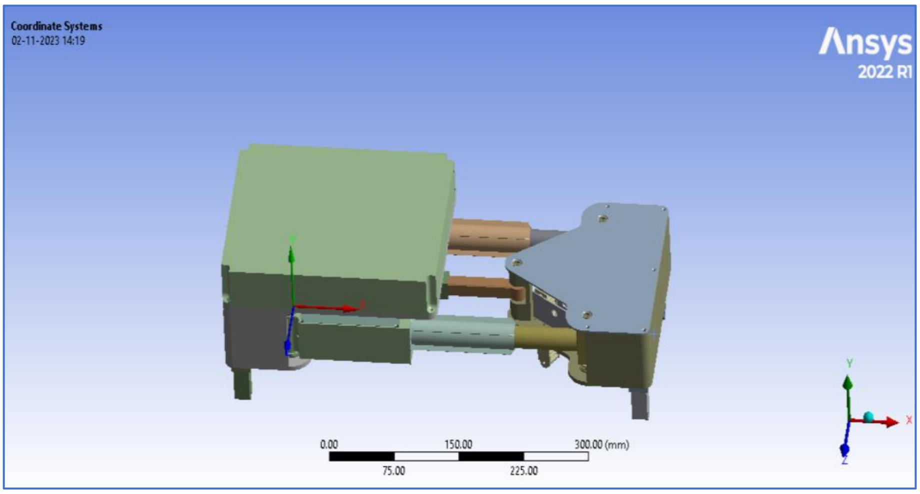


**Figure 4.5: Global Coordinate System**

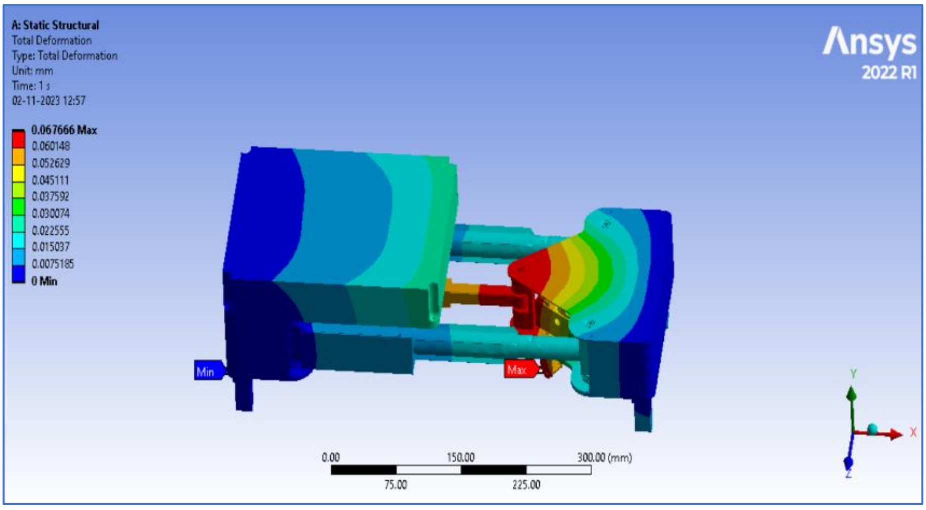


**Figure 4.6: Total Deformation**

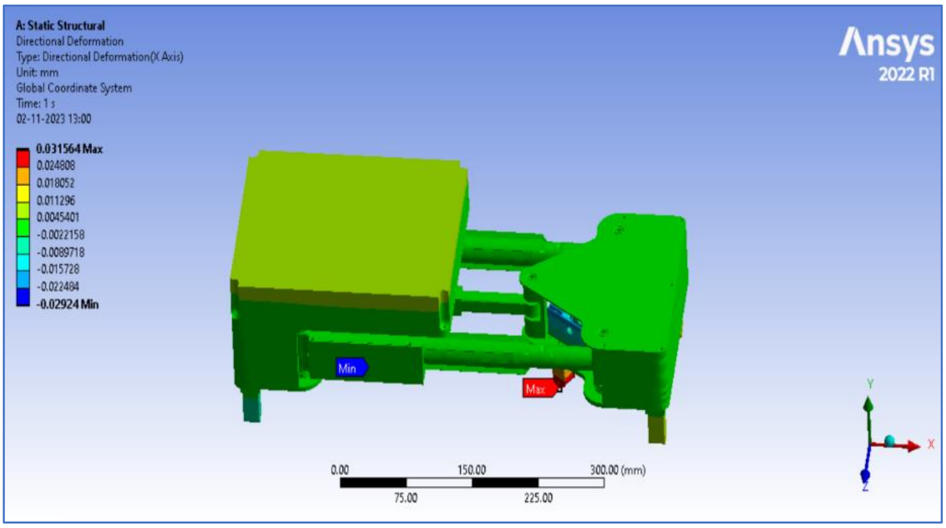


**Figure 4.7: Directional Deformation**

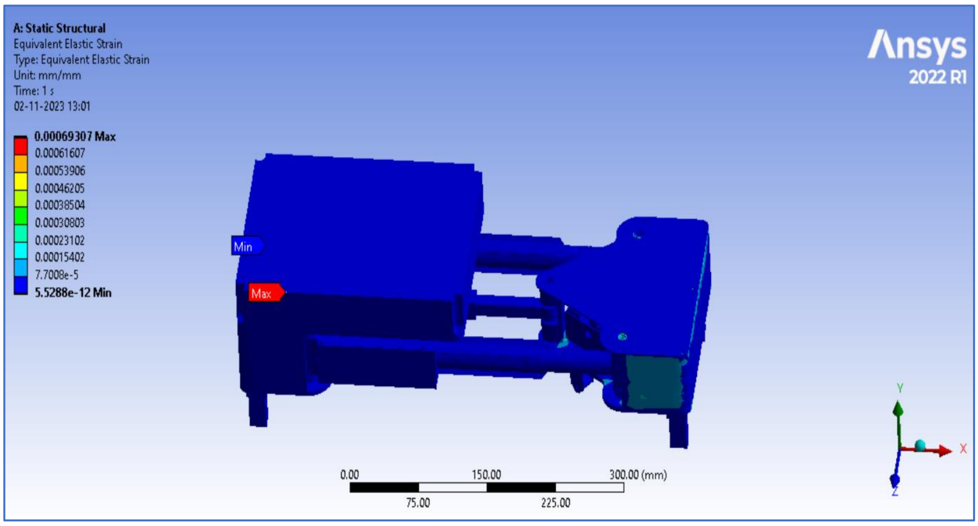


Figure 4.8: Equivalent Elastic Strain

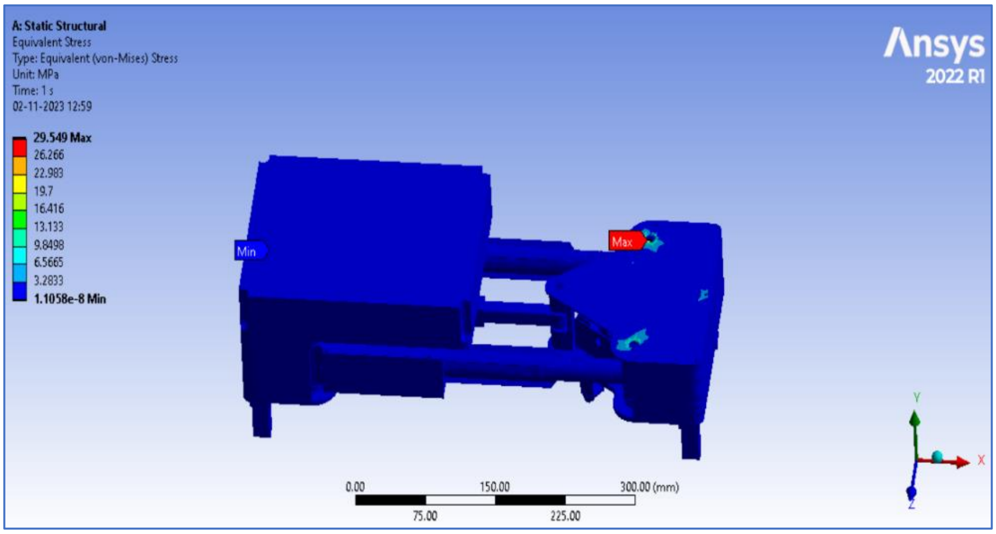


Figure 4.9: Equivalent Stress

### 4.3 Static Structural Analysis of Caterpillar Robot Using ABS Material

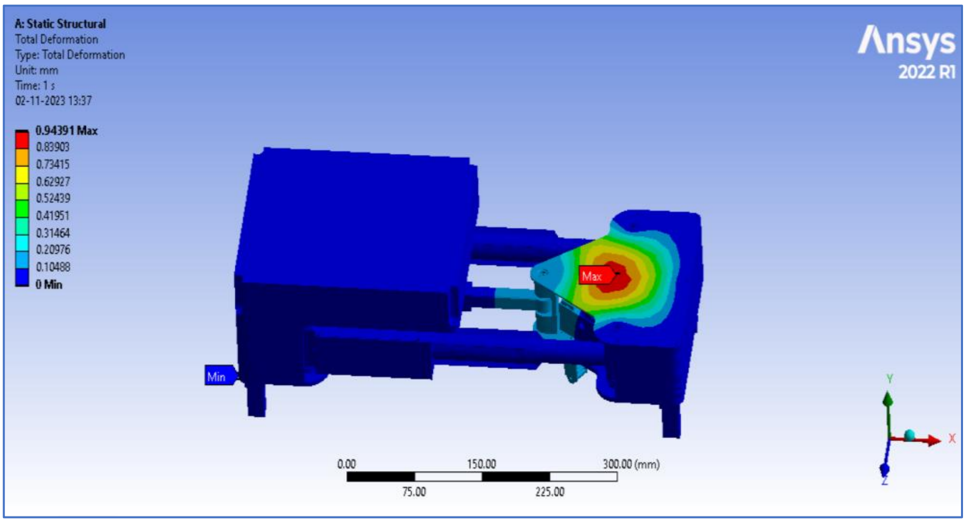

**Figure 4.10: Total Deformation**

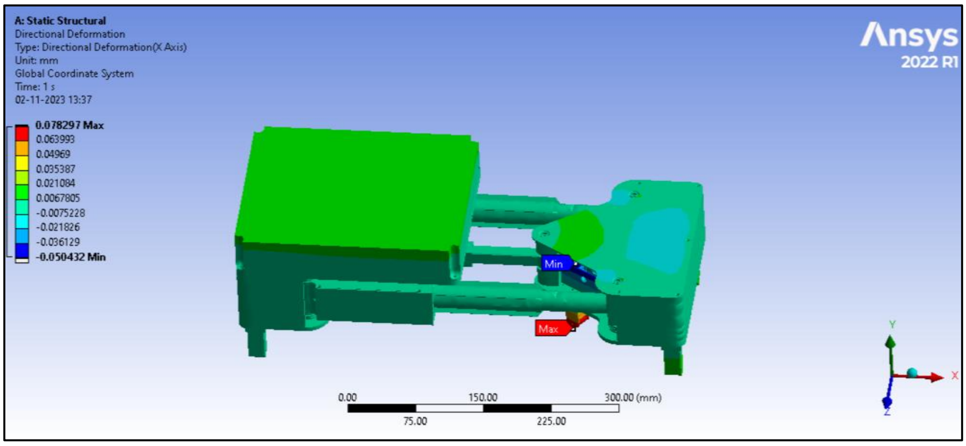


**Figure 4.11: Directional Deformation**

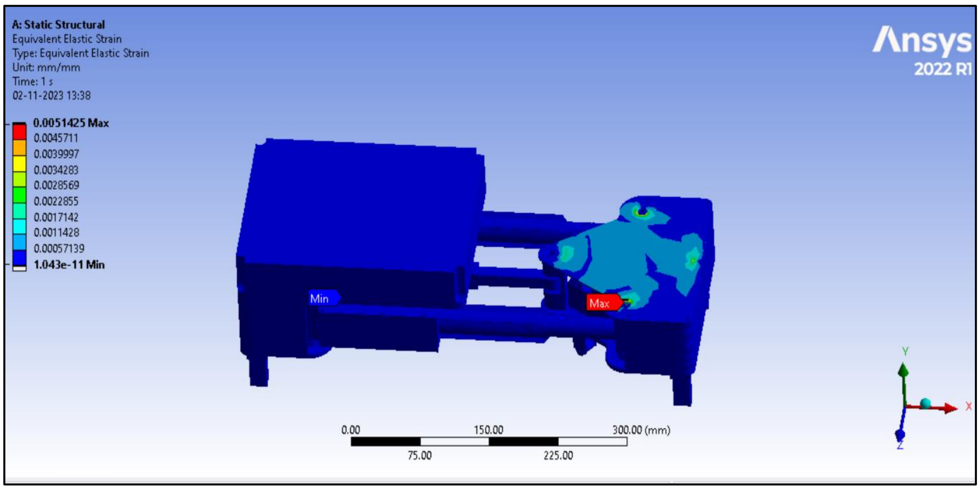


**Figure 4.12: Equivalent Elastic Strain**

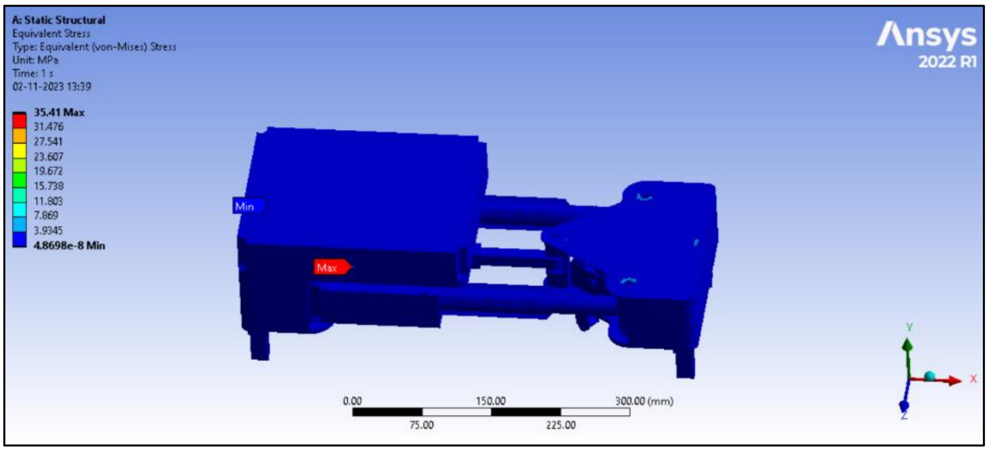


**Figure 4.13: Equivalent Stress**

**Table 4.1: Static structural analysis of caterpillar Robot using different Materials**

| Materials | Total deformation (mm) | Directional deformation (mm) | Equivalent elastic strain | Equivalent Stress (Mpa) |
|---|---|---|---|---|
| PLA | 6.7666 | 3.1564 | 6.9307 | 29.54 |
| ABS | 0.94391 | 7.8297 | 5.1425 | 35.41 |

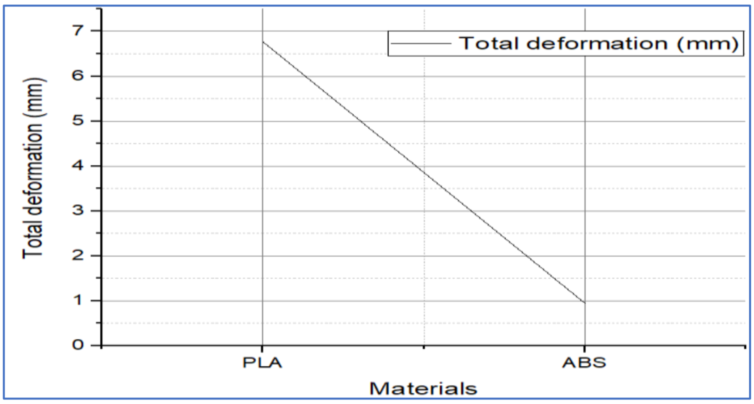


Figure 4.14: Validation of Total Deformation Both Materials

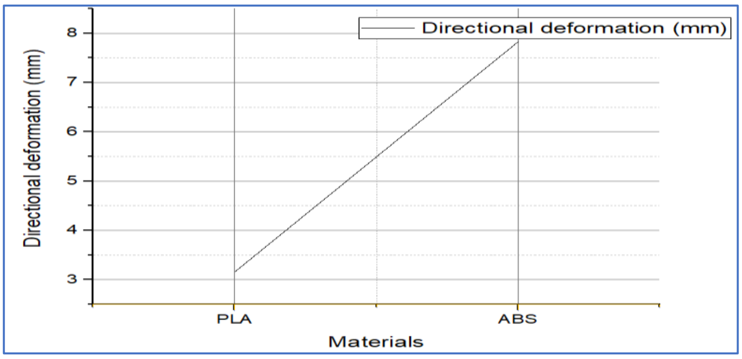


Figure 4.15: Validation of Directional Deformation Both Materials

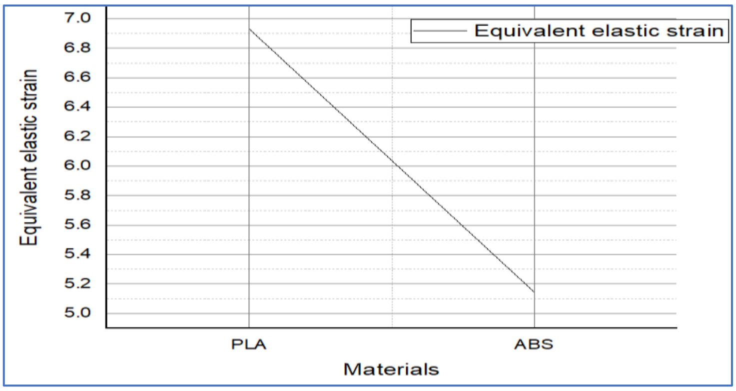


Figure 4.16: Validation of Equivalent Elastic Strain Both Materials

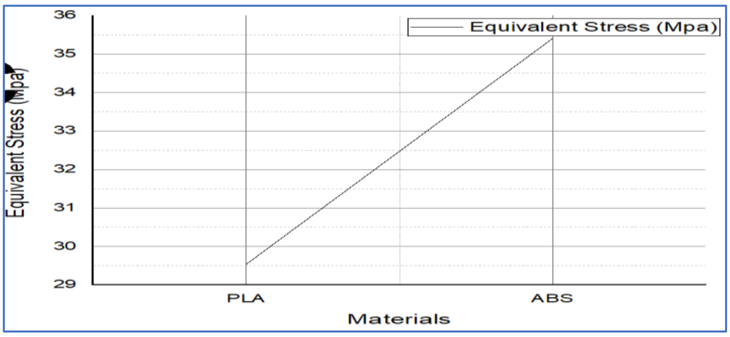


Figure 4.17: Validation of Equivalent Stress Both Materials

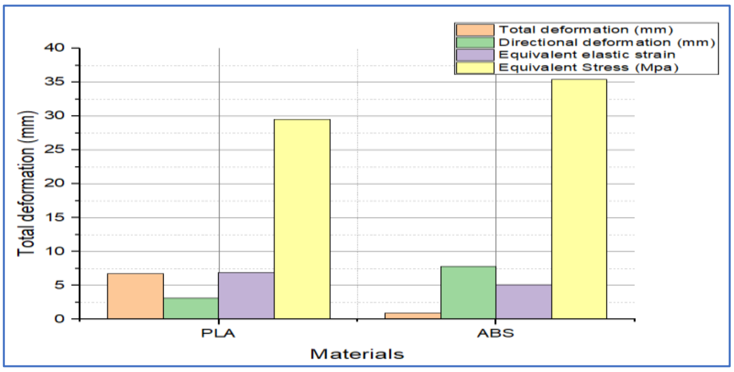


**Figure 4.18: Comparison between PLA and ABS Materials**

**CONCLUSION**

The data graph is focused on the comparison of two materials, ABS and PLA, and how they differ in several deformation and stress categories. The categories compared across these two materials are Total Deformation, Directional Deformation, Equivalent Elastic Strain, and Equivalent Stress. Essential statistical details like average, minimum, maximum, and range values offer insights into how these materials behave under stress.

- The total deformation of ABS is significantly lower than PLA. As a result, ABS may be more resistant to external forces and might undergo less shape change under stress, making it a more durable material.
- PLA demonstrates a remarkably lower directional deformation compared to ABS. This implies that PLA might potentially resist deformation in a particular direction better than ABS. It may stay truer to its original form when subjected to directional forces.
- PLA shows a higher equivalent elastic strain but a lower equivalent stress than ABS. This might indicate that PLA can endure more strain before deforming but deals with fewer stress in the process, possibly making it more suitable for applications requiring flexibility under stress.
- The analysis reveals distinct behavioural characteristics of ABS and PLA when subjected to stress and strain.

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