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Design and static structural analysis of steeped shaft using different composite materials

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Abstract: A stepped shaft is a vital mechanical component commonly used in engineering applications to transmit torque and rotational forces between different machine elements. The design of a stepped shaft involves creating a shaft with varying diameters along its length to accommodate different loading conditions such as axial, torsional, and bending stresses. The choice of material significantly impacts the shaft's performance in terms of strength, stiffness, durability, and weight. Traditionally, materials such as carbon steel, stainless steel, and aluminum alloys are commonly used for stepped shafts. However, advanced composite materials such as Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and Aramid Fiber Reinforced Polymer (AFRP) are gaining popularity due to their superior strength-to-weight ratios, corrosion resistance, and fatigue resistance. This study examines the design and static structural analysis of stepped shafts using different materials, including metals and composites, to assess their performance under various loading conditions. The results highlight the benefits of using composites in applications where high strength-to-weight ratio and corrosion resistance are crucial, while metals remain a preferred choice in heavy-duty applications requiring higher stiffness and mechanical strength.

Keywords: Stepped shaft, Composite materials, Shaft design, Static structural analysis.

Introduction: The design and static structural analysis of stepped shafts using composite materials has become an important research area because of the increasing requirement for lightweight and high-strength mechanical transmission systems in automotive and aerospace industries. Conventional metallic shafts generally possess higher weight and are more prone to corrosion and fatigue failures under variable loading conditions. Researchers have therefore investigated the use of composite materials such as carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), Kevlar composites, and hybrid laminates for stepped shaft applications. Studies reported that composite shafts provide significant weight reduction while maintaining excellent torsional stiffness and strength characteristics (Gupta and Lal, 2019; Reddy and Rao, 2020). Finite Element Analysis (FEA) tools such as ANSYS and ABAQUS are widely utilized to analyze stress distribution, deformation, and structural stability under static loading conditions (Sharma and Singh, 2021). The literature also emphasizes that parameters such as fiber orientation, stacking sequence, shaft geometry, and fiber volume fraction strongly influence the overall mechanical behavior of stepped composite shafts (Wang et al., 2020; Ahmed and Khan, 2019). ecent investigations further indicate that hybrid composite shafts exhibit better vibration damping, improved fatigue resistance, and enhanced buckling strength compared with conventional steel shafts. Comparative studies demonstrated that composite shafts can achieve weight reductions between 40% and 75% while maintaining comparable or superior mechanical performance (Kim et al., 2022). Researchers specifically focused on stepped shafts because stress concentration occurs at shoulder fillets and diameter transition regions, which may lead to structural failure under static and cyclic loading conditions (Patel and Joshi, 2021). Optimization techniques including genetic algorithms and topology optimization methods have been employed to improve shaft performance and minimize stress concentration effects (Lee and Park, 2018; Martinez and Chen, 2024). Furthermore, studies showed that carbon/epoxy composites provide higher stiffness and lower deformation compared with glass/epoxy composites, whereas hybrid laminates offer a balanced combination of cost and performance (Kumar et al., 2022; Zhou et al., 2021). These findings suggest that composite stepped shafts are highly suitable for modern engineering applications requiring lightweight construction, improved structural efficiency, and enhanced durability (Prasad and Verma, 2023).

2. Scope of the Work

This study focuses on the design and static structural analysis of a stepped shaft using a variety of materials, including traditional metals and advanced composites such as CFRP, GFRP, and AFRP. The scope includes Modeling the stepped shaft with varying diameters in SolidWorks 2026 and conducting static structural analysis in ANSYS 2025 R2 to evaluate the shaft's performance under different loading conditions, including axial, torsional, and bending

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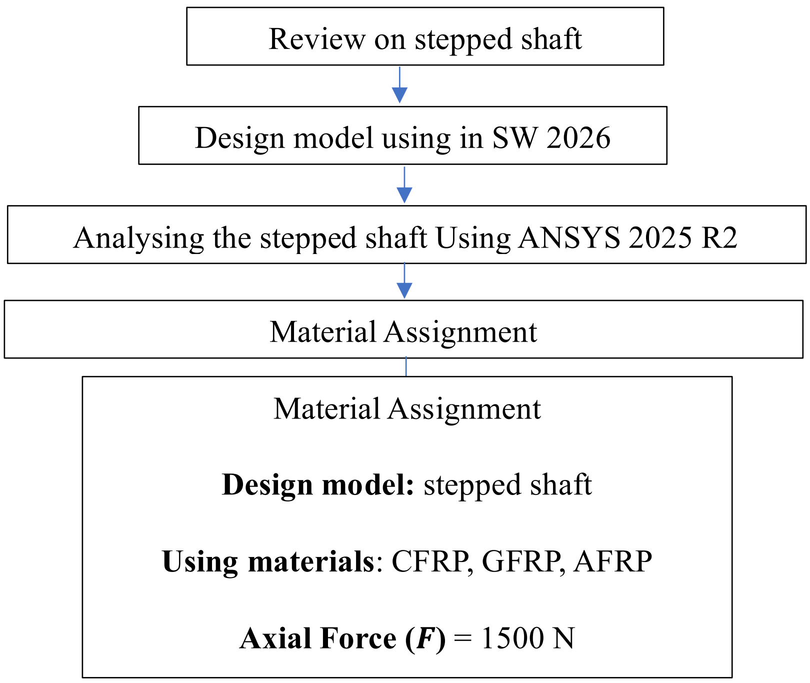
stresses. The analysis will compare the stress distribution, deformation, and factor of safety for each material to identify the most suitable material based on specific application requirements.

2.1 Problem Statement:

The design of a stepped shaft is crucial for ensuring the reliable transmission of torque and forces in mechanical systems. Traditional materials like metals often offer high strength but may come with limitations in terms of weight, corrosion resistance, and fatigue resistance. With the increasing demand for lightweight, durable, and efficient mechanical components, there is a need to explore advanced materials, such as composite materials, to optimize the performance of stepped shafts. The problem addressed in this study is the comparison of different materials metals and composites in the design of a stepped shaft, focusing on their performance under various loading conditions. Specifically, the study aims to evaluate the effectiveness of composite materials (CFRP, GFRP, AFRP) in comparison to traditional metals, in terms of stress distribution, deformation, and overall mechanical efficiency.

3.Methodology

The methodology involves the design and static structural analysis of a stepped shaft using different materials, including Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), Aramid Fiber Reinforced Polymer (AFRP), and traditional metals. The shaft geometry is modeled in SolidWorks 2026, incorporating varying diameters along its length to optimize performance under axial, torsional, and bending loads. Following steps:



Validate total deformation, stress, strain → Conclusion

Working Principles of a Stepped Shaft

A stepped shaft is a mechanical component that is commonly used to transmit torque and rotational motion between different parts of a machine, such as gears, pulleys, and bearings. The design of a stepped shaft includes varying diameters along its length to accommodate different load-bearing needs and to ensure the proper functioning of the system it is a part of.

The working principles of a stepped shaft can be broken down into the following key concepts:

1. Torque Transmission

The primary function of a stepped shaft is to transmit torque from one part of a machine to another. The torque is applied at one end of the shaft, and due to the rotational motion, it is passed along the length of the shaft to the other end. The shaft's design, with different diameters (steps), allows it to connect components of various sizes while ensuring that the transmitted torque is efficiently handled.

- **Torsional Loading**: When a torque is applied to the shaft, it experiences torsional stress, which results in twisting. The design of the shaft, including material selection and diameter changes, helps manage the twisting forces effectively.

2. Load Distribution

In a stepped shaft, different parts of the shaft are designed to carry different amounts of load, depending on the specific requirements of the machine.

- **Axial Load**: This is a load that acts along the axis of the shaft. It can either be tensile (pulling) or compressive (pushing) and is typically transmitted along the full length of the shaft. The stepped design allows for optimal load-bearing by adjusting the diameter and material strength in different regions.
- **Radial Load**: This load acts perpendicular to the axis of the shaft and is typically caused by gears or pulleys mounted on the shaft. The stepped regions, with varying diameters, help distribute radial loads efficiently across different sections of the shaft.

3. Bending and Shear Stresses

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The stepped shaft may also be subjected to bending and shear stresses, especially when it is not aligned with the axis of rotation or when external loads cause deflection.

- **Bending Stress**: Bending occurs when forces applied perpendicular to the shaft cause it to bend. This results in stress at the outermost part of the shaft. The stepped design helps in minimizing the bending by providing different diameters that increase resistance to bending in critical areas.
- **Shear Stress**: The shear force is experienced by the shaft due to torque. The stepped design helps reduce the shear stress by distributing the load over different sections of the shaft.

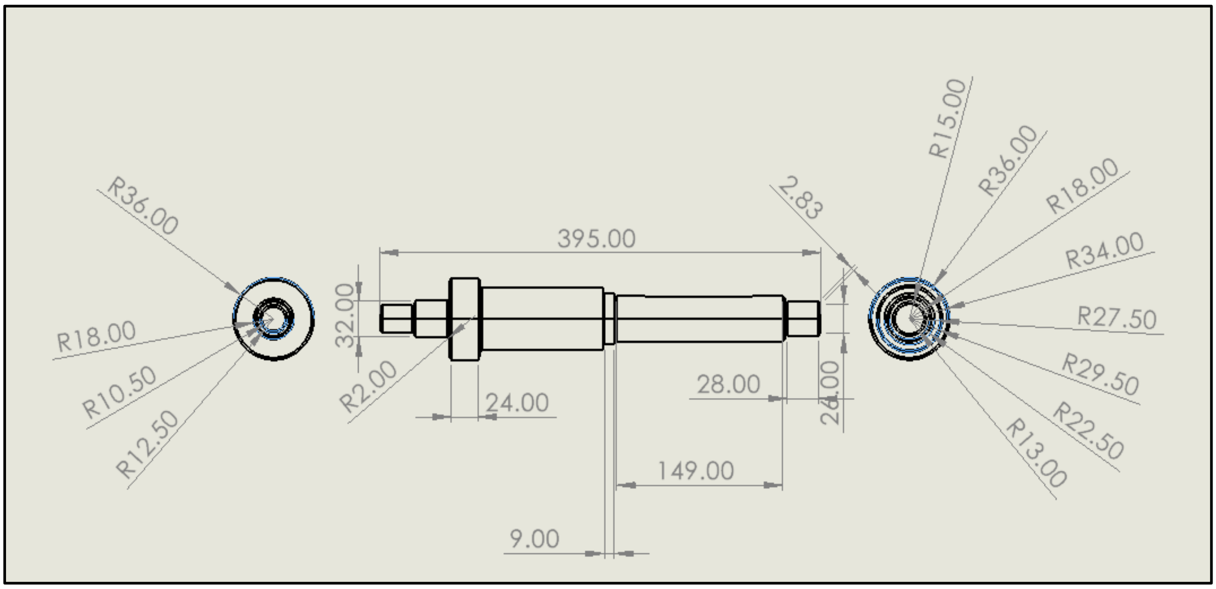

Figure:1 Geometry model

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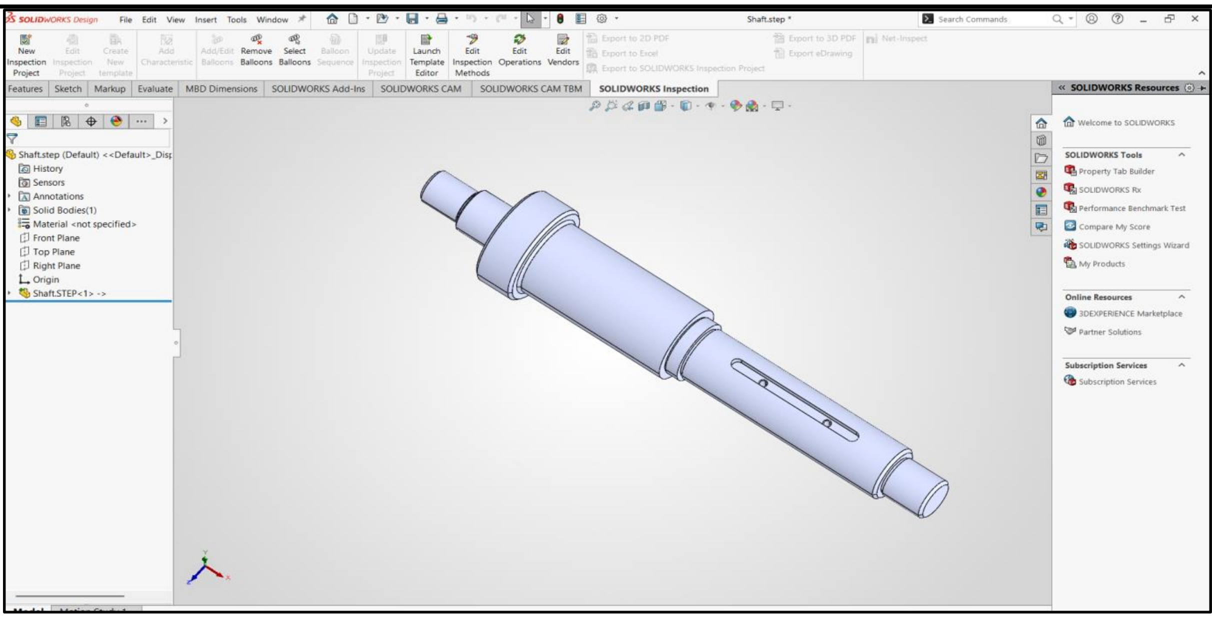

Figure:2 Stepped shaft

The Figure shows a technical drawing of a stepped shaft, a common component in mechanical systems. This shaft features multiple diameter changes along its length, designed to handle various mechanical stresses, such as axial, torsional, and bending forces. The dimensions and radii indicated in the drawing correspond to specific features of the shaft, such as the different step sizes and the radii at the shaft ends.

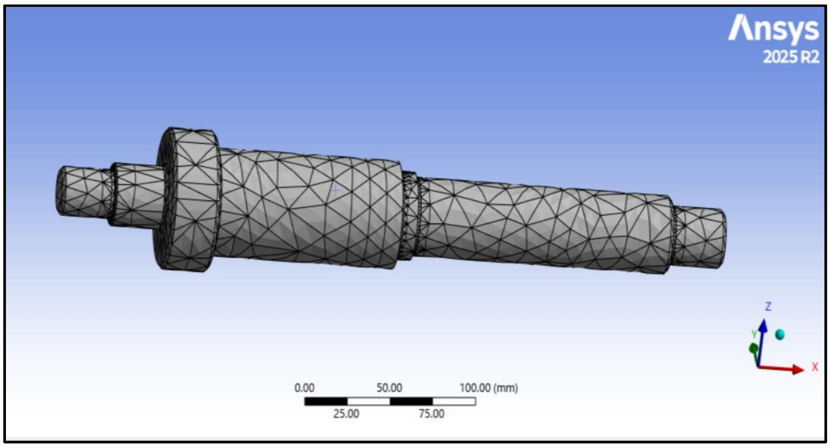

Figure 3: Meshed model

4. RESULTS AND DISCUSSIONS

The results from the static structural analysis of the stepped shaft indicate the performance of the component under the applied axial load of 1500 N, considering three different materials: Carbon Steel, Stainless Steel, and Cast Iron. The analysis provides insights into the total deformation, stress distribution, and strain patterns across the shaft.

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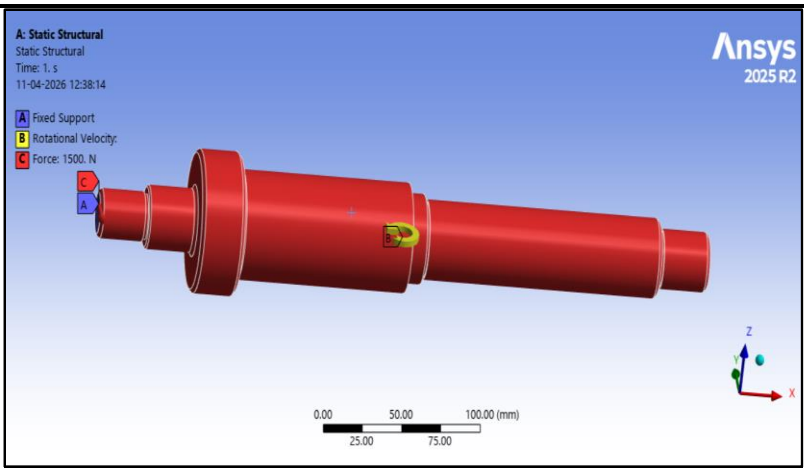

Figure 4: Stepped shaft applied boundary conditions

The figure shows the stepped shaft model in ANSYS 2025 R2 with applied boundary conditions for the static structural analysis. The fixed support (point A) is applied at one end of the shaft to simulate the mounting or anchoring of the shaft in a mechanical system. An axial force of 1500 N (point C) is applied along the shaft to replicate the operational loading condition.

Static structural analysis of stepped shaft using carbon steel 1020 material

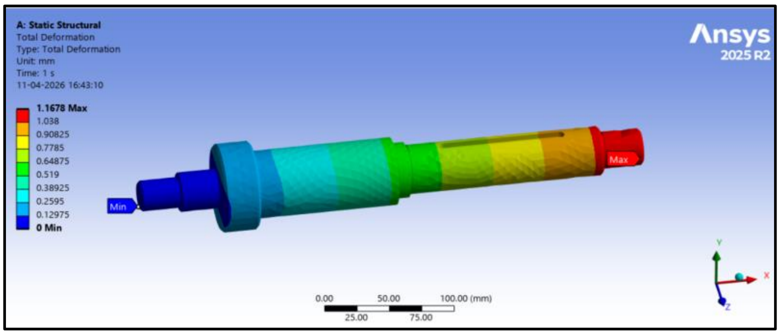

Figure 5: Total deformation in mm

The figure displays the total deformation analysis of the stepped shaft under an applied axial force of 1500 N using Carbon Steel 1020 material. The analysis shows that the deformation is concentrated at specific locations along the shaft, especially at the transitions between different diameters, where stress concentrations tend to occur.

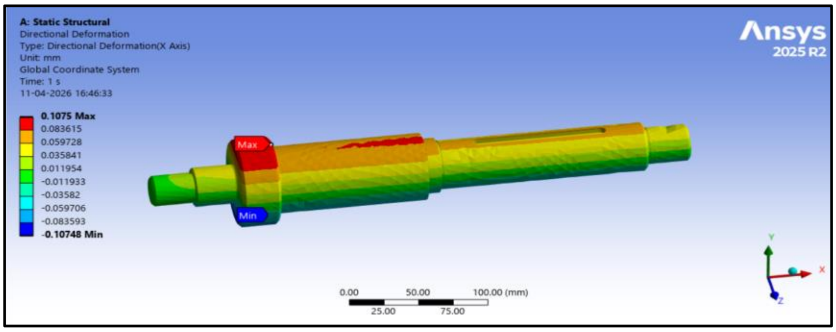

Figure 6: Directional deformation in mm

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The figure displays the directional deformation along the X-axis for the stepped shaft under an applied axial force of 1500 N using Carbon Steel 1020 material. The deformation is shown in millimeters and is represented by a color map where red indicates the maximum deformation of 0.1075 mm, and blue represents the minimum deformation, with values approaching -0.10748 mm.

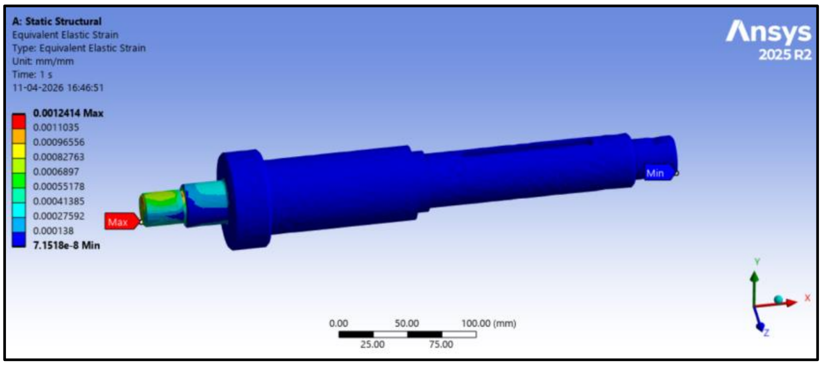

Figure 7: Equivalent strain

The figure 7 shows the equivalent elastic strain of the stepped shaft under an applied axial force of 1500 N, using Carbon Steel 1020 material. The maximum strain value of 0.0012141 mm/mm is shown in red at the region where deformation is most pronounced, while the minimum strain value of 7.1518e-8 mm/mm is shown in blue at the shaft's other regions.

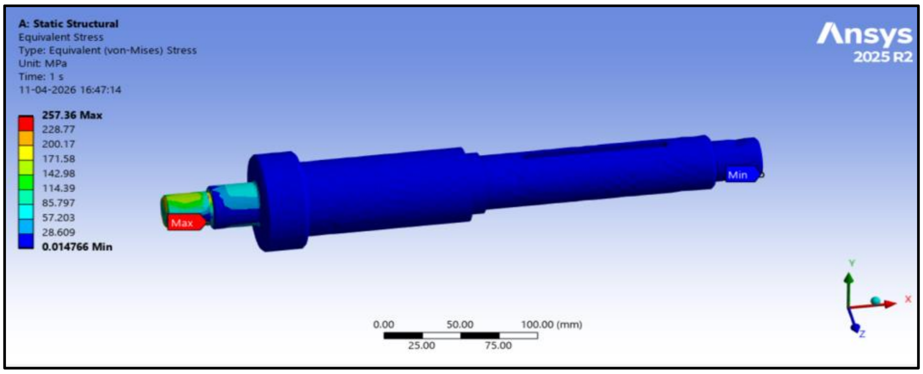

Figure 8: Equivalent stress

The figure displays the equivalent (von-Mises) stress distribution for the stepped shaft under an applied axial force of 1500 N, using Carbon Steel 1020 material. The maximum stress value of 257.36 MPa is highlighted in red at the transition areas between different diameters of the shaft, where stress concentration typically occurs. The minimum stress value of 0.014766 MPa is shown in blue, indicating areas of the shaft experiencing little to no stress.

Static structural analysis of stepped shaft using SS316 material

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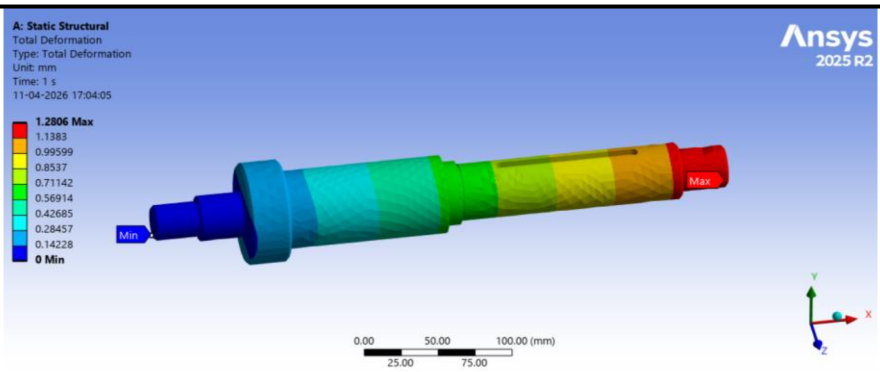

Figure 9: Total deformation in mm

The figure displays the total deformation of the stepped shaft using SS316 (Stainless Steel 316) material under an applied axial force of 1500 N. The maximum deformation of 1.2806 mm is observed at the shaft's transition point, marked in red, while the minimum deformation of 0 mm is shown in blue at the fixed support end.

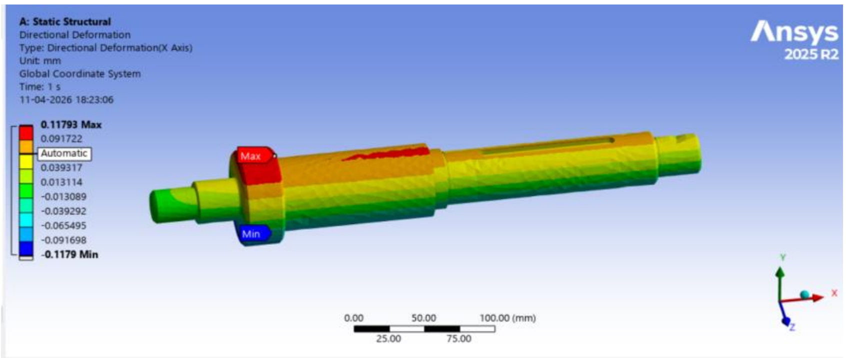

Figure 10: Directional deformation in mm

The figure shows the directional deformation of the stepped shaft under an applied axial force of 1500 N, using SS316 (Stainless Steel 316) material, along the X-axis. The maximum deformation of 0.11793 mm is shown in red at the end of the shaft, while the minimum deformation of -0.11793 mm is shown in blue at the fixed support end.

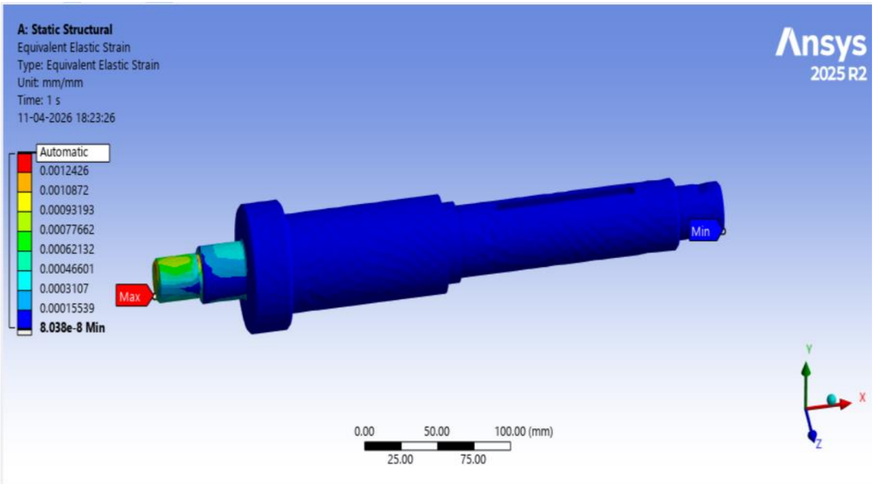

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Figure 11: Equivalent strain

The figure shows the equivalent elastic strain for the stepped shaft under an applied axial force of 1500 N, using SS316 (Stainless Steel 316) material. The maximum strain value of 0.0012426 mm/mm is represented in red at the shaft's transition area, while the minimum strain of 8.038e-8 mm/mm is shown in blue at the fixed support end.

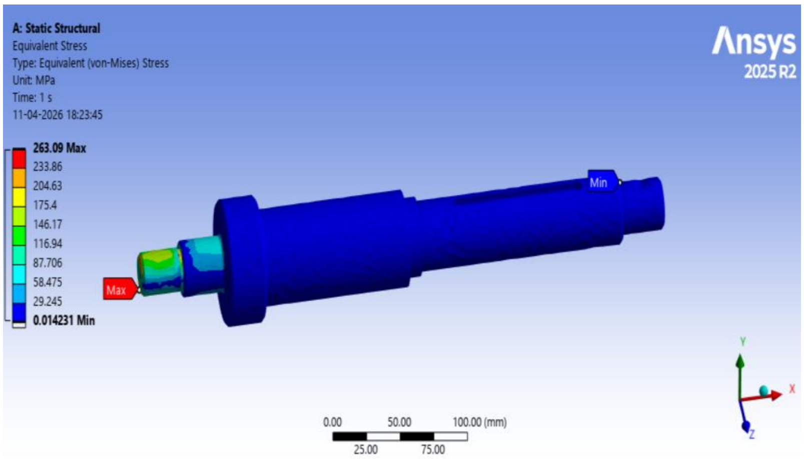

Figure 12: Equivalent stress

The figure shows the equivalent (von-Mises) stress distribution for the stepped shaft using SS316 (Stainless Steel 316) material, subjected to an applied axial force of 1500 N. The maximum stress value of 263.09 MPa is highlighted in red at the shaft's transition areas, particularly where the diameter changes. The minimum stress of 0.014231 MPa is shown in blue at the fixed support end, indicating that this region experiences minimal stress.

Static structural analysis of stepped shaft using Gray cast iron material

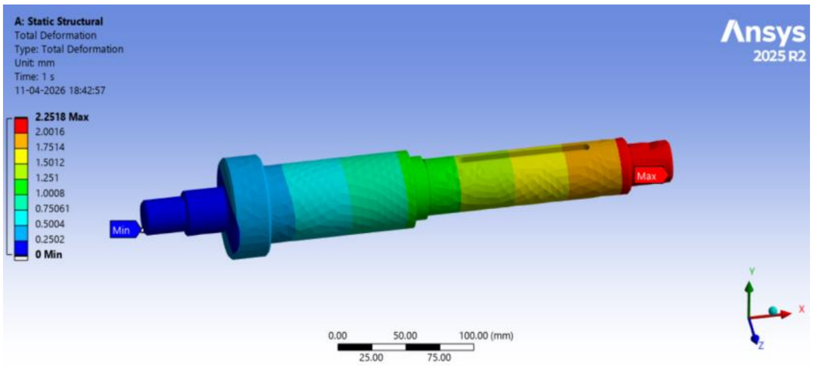

Figure 13: Total deformation in mm

The figure shows the total deformation distribution of the stepped shaft made of Gray Cast Iron under applied loading conditions. The deformation is represented using a color contour scale, where blue

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indicates minimum deformation and red indicates maximum deformation. From the analysis, the maximum deformation of approximately 2.2518 mm occurs at the free end of the shaft, which is expected due to the applied load and lack of support at that region.

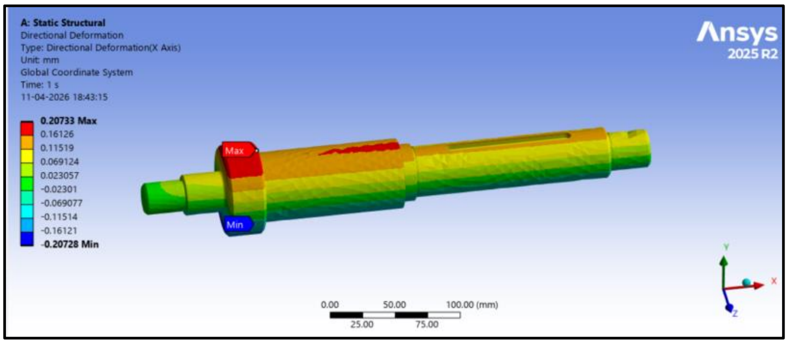

Figure 14: Directional deformation in mm

The figure represents the directional deformation of the stepped shaft along the X-axis under static loading conditions. From the contour plot, the maximum directional deformation is approximately +0.20733 mm, observed near the shoulder region, while the minimum deformation is around -0.20728 mm, indicating displacement in the opposite direction

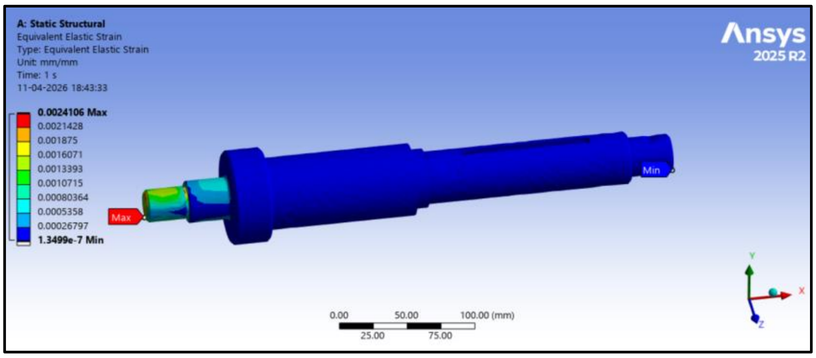

Figure 15: Equivalent strain

The figure illustrates the equivalent elastic strain distribution in the stepped shaft made of Gray Cast Iron the maximum equivalent strain is approximately 0.0024106 mm/mm, observed near the smaller diameter region close to the fixed end, where stress concentration is higher due to geometric discontinuity. The minimum strain ($\approx 1.3499 \times 10^{-7}$ mm/mm) occurs at regions far from load application and stress concentration zones.

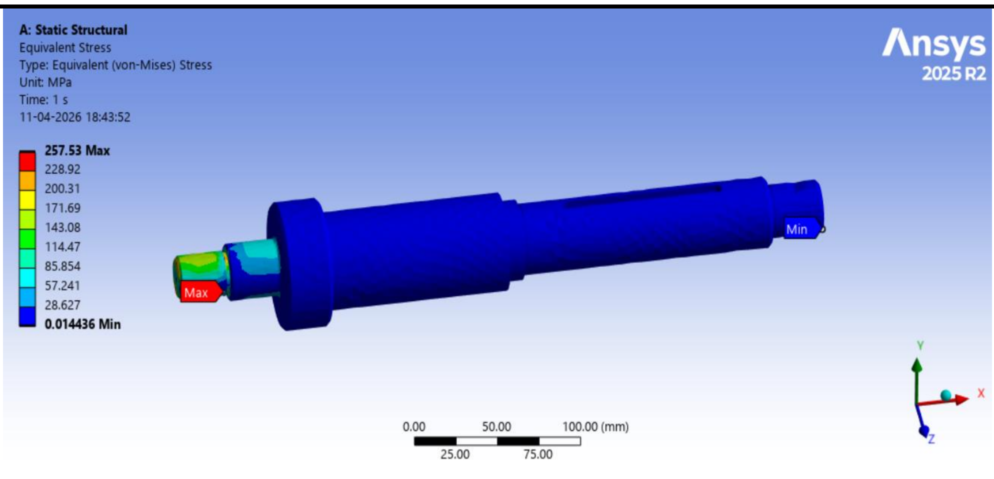

Figure 16: Equivalent stress

The figure shows the equivalent (von Mises) stress distribution in the stepped shaft made of Gray Cast Iron under static loading conditions. From the contour plot, the maximum stress is approximately 257.53 MPa, observed near the smaller diameter region close to the step, indicating a high stress concentration zone. The minimum stress (~0.014 MPa) is found at regions far from the load and constraint locations.

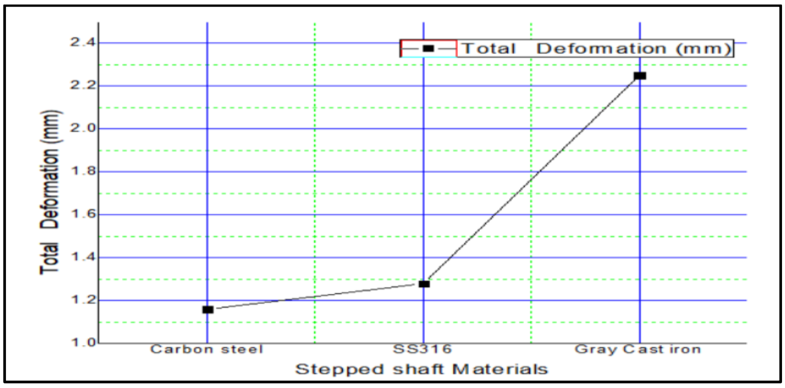

Figure 17: Validation of stepped shaft Total Deformation (mm) results

The figure17 compares the total deformation of a stepped shaft using different materials. It is observed that Gray Cast Iron shows the highest deformation (~2.25 mm), followed by SS316 (~1.27 mm), while Carbon Steel exhibits the least deformation (~1.15 mm). This variation is due to differences in material stiffness, where carbon steel provides greater resistance to deformation. The results highlight the importance of material selection in ensuring structural strength and performance.

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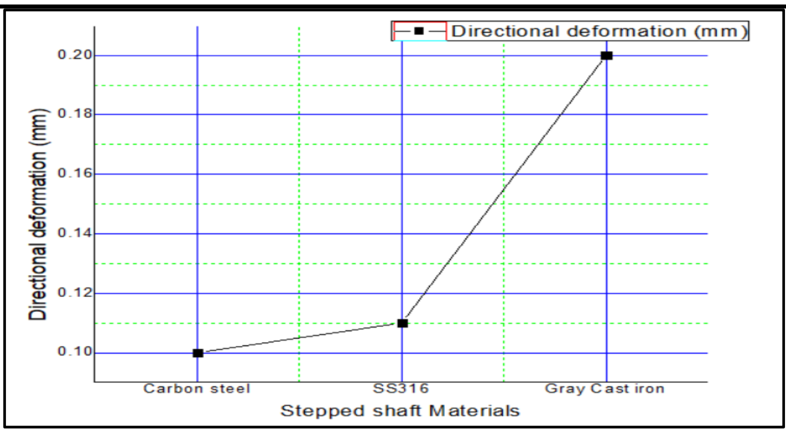

Figure 18: Validation of stepped shaft directional Deformation (mm) results

The figure shows the comparison of directional deformation of the stepped shaft for different materials. It is observed that Gray Cast Iron has the highest directional deformation (~0.20 mm), followed by SS316 (~0.11 mm), while Carbon Steel shows the lowest (~0.10 mm). This indicates that carbon steel provides better resistance to axial displacement due to its higher stiffness. The results emphasize that material selection significantly affects the directional deformation behavior of the shaft

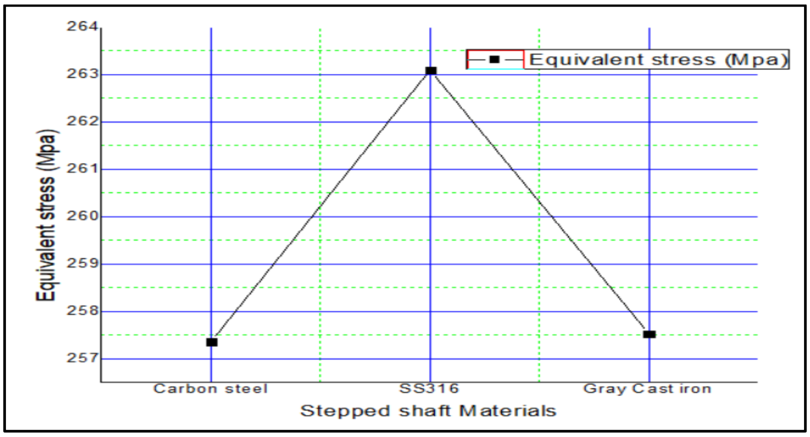

Figure 19: Validation of stepped shaft equivalent stress (Mpa) results

The figure compares the equivalent (von Mises) stress of the stepped shaft for different materials. It is observed that SS316 shows the highest stress (~263 MPa), while Carbon Steel and Gray Cast Iron exhibit nearly similar lower stress values (~257 MPa). This indicates that SS316 experiences slightly higher stress under the same loading conditions. The results highlight that although deformation varies significantly with material, the stress distribution remains relatively close, with slight variation due to differences in material properties.

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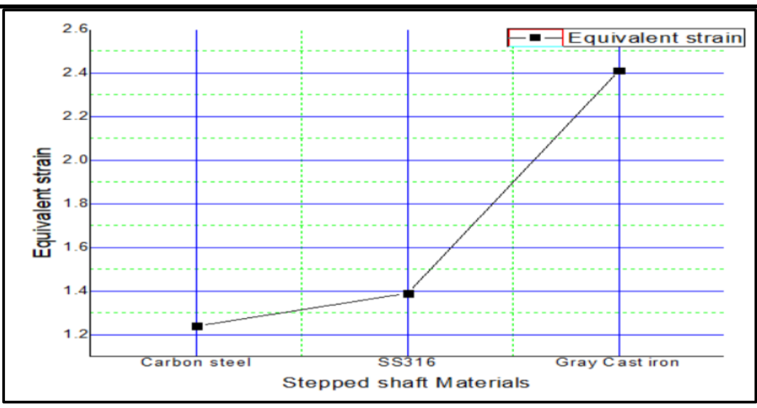

Figure: 20 Validation of stepped shaft equivalent strain results

The figure shows the comparison of equivalent strain for the stepped shaft using different materials. It is observed that Gray Cast Iron exhibits the highest strain (~2.4×10^{-3}), followed by SS316 (~1.4×10^{-3}), while Carbon Steel shows the lowest strain (~1.25×10^{-3}). This indicates that gray cast iron undergoes more deformation per unit length, making it less resistant to strain. The results emphasize that materials with higher stiffness, like carbon steel, experience lower strain and are more suitable for applications requiring strength and durability.

5. Conclusions

The static structural analysis of the stepped shaft using different materials clearly demonstrates the critical role of material properties in determining the mechanical performance of the component. Among the materials analyzed, carbon steel exhibits the least total deformation and equivalent strain, indicating its superior stiffness and ability to withstand applied loads with minimal displacement. SS316 shows moderate performance, with slightly higher stress values but controlled deformation, making it a balanced choice where corrosion resistance is also required. In contrast, Gray cast iron experiences the highest deformation and strain, which is attributed to its comparatively lower stiffness and brittle nature, making it more susceptible to deformation under identical loading conditions. The results also reveal that equivalent (von Mises) stress values are relatively close for all materials, with only slight variations, suggesting that stress distribution is primarily influenced by geometry and loading rather than material stiffness alone. However, the maximum stress and strain concentrations are consistently observed at the stepped or shoulder regions of the shaft, which act as critical points due to sudden changes in cross-sectional area. These regions are more prone to failure, especially in brittle materials like Gray cast iron, where crack initiation is more likely. Overall, the study concludes that carbon steel is the most suitable material for stepped shaft applications requiring high strength, rigidity, and durability, while SS316 can be preferred for environments demanding corrosion resistance with acceptable mechanical performance. Gray cast iron, although beneficial for its damping capacity, is less ideal for high-load applications due to its higher deformation and strain characteristics. Therefore, proper material selection combined with design optimization such as adding fillets or reducing stress concentration at stepped regions is essential to enhance the safety, reliability, and service life of the shaft.

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