International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Comparative Analysis of Beams in Curved in Plan with Varying Cross Section

Mr. Ganesh S. Tatikonda
Prof. Rameez R. Badeghar

Head of Department, Civil Engineering, Swami Vivekanand Institute of Technology, Solapur

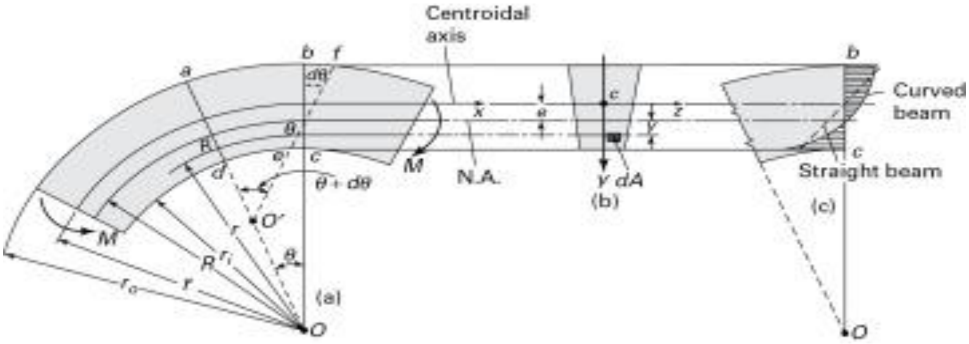
Abstract
Curved beams in plan are widely adopted in modern structural systems due to their geometric adaptability and enhanced load transfer mechanisms. However, their structural response becomes significantly nonlinear and complex when coupled with spatial curvature and varying cross-sections. This study presents a detailed comparative investigation of prismatic straight beams, prismatic curved beams, and non-prismatic curved beams with variable cross-sectional properties. The analysis focuses on stress distribution, deformation characteristics, and structural efficiency under identical loading and boundary conditions.
A three-dimensional finite element formulation is implemented using ANSYS 2025 R1, employing higher-order solid elements to capture the combined effects of bending, torsion, and axial stresses. A parametric study is conducted by varying the radius of curvature to quantify its influence on stress concentration and deflection behavior.

Keywords: Curved beams, Non-prismatic beams, Finite element analysis (FEA), ANSYS 2025 R1, Stress distribution, Structural efficiency, Winkler–Bach theory, Parametric analysis, Beam curvature.

1. Introduction

Beam elements constitute one of the most fundamental components in structural engineering, playing a critical role in transferring loads and maintaining the stability and integrity of structures. Traditionally, most structural analyses and designs are based on straight (prismatic) beams with uniform cross-sections, primarily due to their analytical simplicity and well-established theoretical background based on Euler–Bernoulli beam theory. However, with the growing demand for innovative architectural forms and efficient structural systems, the use of curved beams in plan has become increasingly prevalent in modern infrastructure such as bridges, flyovers, and large-span roof systems.

Figure 1.1 Stress Distribution in a Curved Beam



Unlike straight beams, curved beams exhibit complex structural behavior due to the presence of curvature, which introduces additional effects such as torsion, non-uniform stress distribution, and a shift in the neutral axis. The classical Winkler–Bach theory provides a framework for analyzing curved beams, accounting for the variation in circumferential stress across the cross-section. However, the analytical treatment of curved beams becomes significantly more challenging when the cross-section varies along the length, resulting in non-prismatic members. In such cases, the moment of inertia and sectional properties are functions of position, leading to highly nonlinear stress and deformation responses.

Non-prismatic curved beams offer significant advantages in terms of material optimization and structural efficiency, as the cross-sectional geometry can be tailored to match the distribution of internal forces. Despite these advantages, their practical application remains limited due to the lack of simplified analytical solutions and standardized design guidelines. Consequently, advanced numerical methods such as finite element analysis (FEA) have become essential tools for accurately predicting their behavior.

In this study, a comprehensive comparative analysis is carried out on straight beams, curved beams, and curved beams with varying cross-sections. A three-dimensional finite element model is developed using ANSYS 2025 R1 to evaluate stress distribution and deformation characteristics under consistent loading and boundary conditions. The numerical results are further validated with established analytical theories to ensure reliability. Additionally, a parametric investigation is performed by varying the radius of curvature to assess its influence on structural response.

The objective of this research is to provide a deeper understanding of the behavior of non-prismatic curved beams and to demonstrate their potential advantages over conventional beam configurations in terms of performance and material efficiency. The findings of this study aim to support the rational design and optimization of complex structural elements in modern engineering applications.

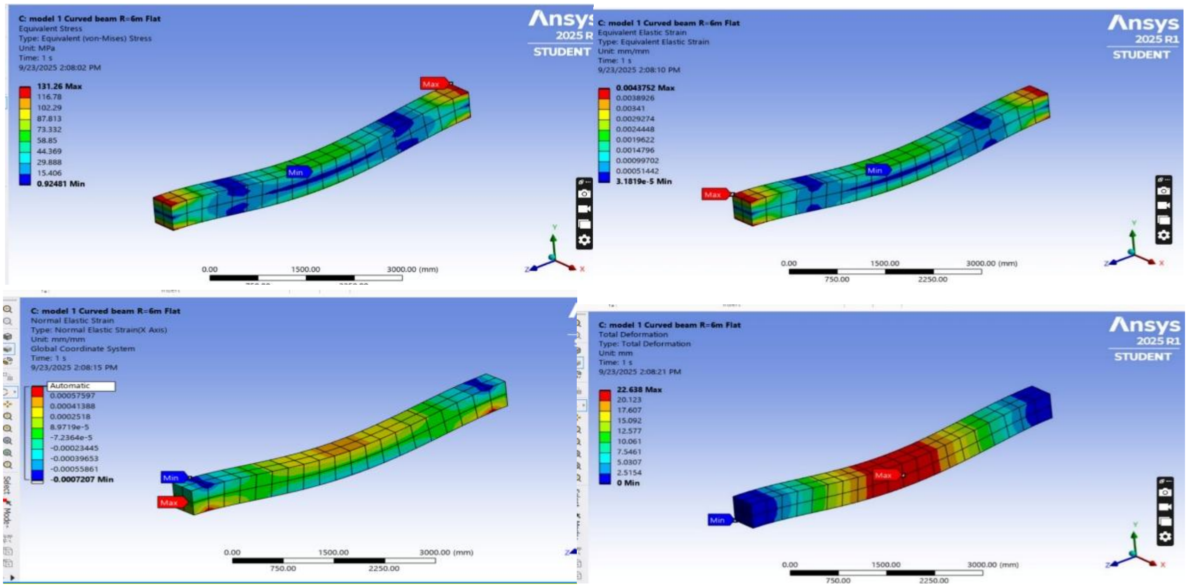
2. Problem Statement

Beams with curved geometry are commonly used in civil engineering structures, especially in bridges, curved walls, and other architectural applications. However, the analysis of such beams, particularly those with varying cross-sectional shapes, presents several complexities. The geometry of the beam, along with the varying cross-section, introduces different stress distributions and behaviors under loading conditions. This research aims to conduct a comparative analysis of beams that are curved in plan with varying cross-sections, as depicted in the provided figure. The main goal is to investigate the impact of varying cross-sectional dimensions on the structural performance of curved beams, focusing on parameters like bending moments, shear forces, and deflection. The study will assess different configurations of these beams with varying cross-sectional profiles and will compare their performance to identify optimal solutions for structural design. This analysis will help in understanding how the curvature and cross-sectional variation influence the beam's structural efficiency and overall behavior under various loading scenarios.

3. Analysis in Ansys

3.1 FLAT BEAM

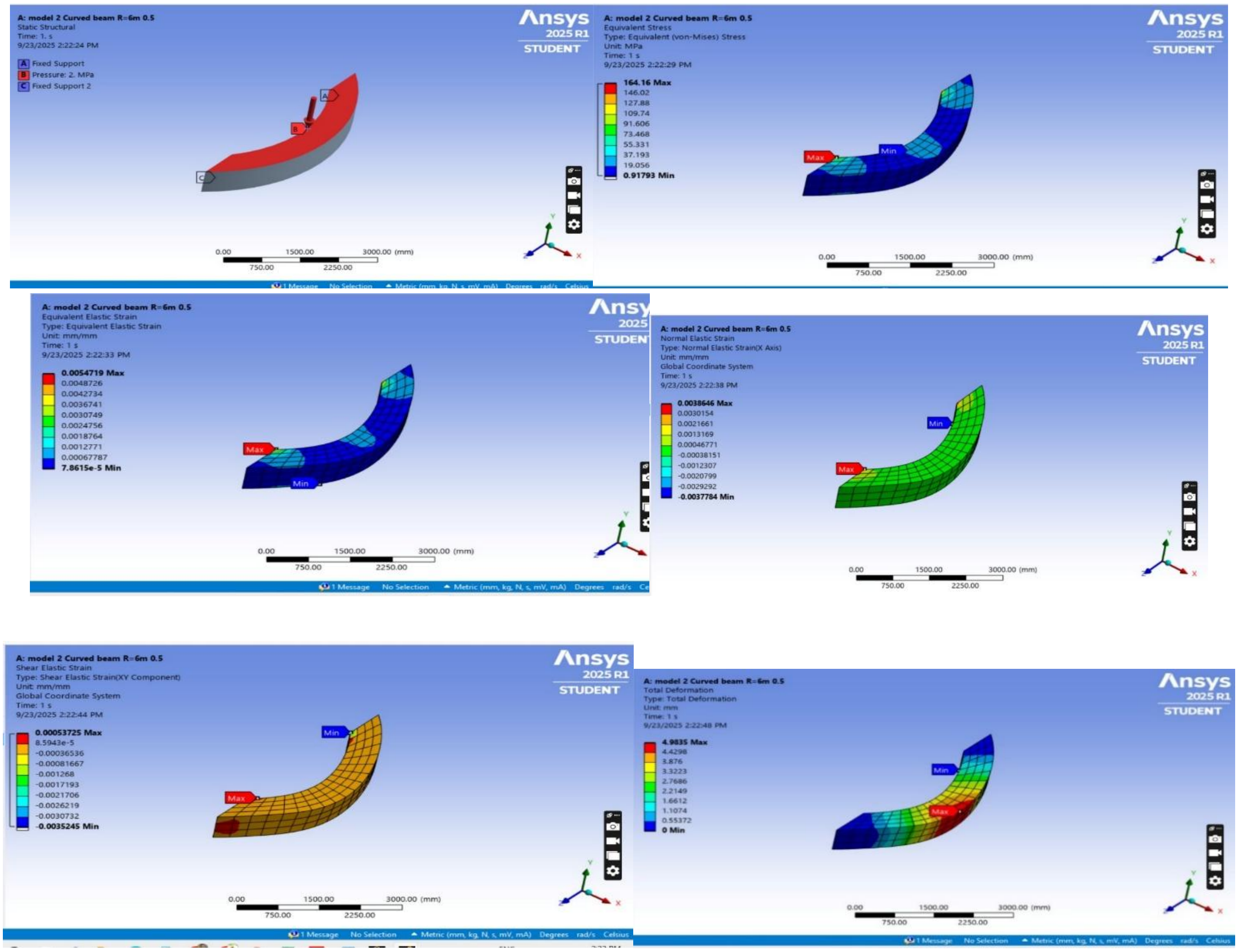
Figure 3.1 Analysis in ansys of flat Beam (Flat Configuration).



- the maximum stress value of 131.26 MPa occurs near the outer edge of the curvature, while the minimum stress of 0.92481 MPa appears at the mid-span region. The stress gradient indicates higher tension at the outer bend and compression on the inner side.
- The maximum strain is 0.0043752 mm/mm located near the outer edge, while the minimum strain is 3.1819e-5 mm/mm at the inner curve. The results indicate bending deformation due to applied loading.
- The maximum strain value observed is 0.00057597 mm/mm, while the minimum strain is -0.0007207 mm/mm. The strain variation along the beam indicates tension on the outer curve and compression on the inner curve.
- The maximum deformation is 22.638 mm observed at the mid-span region, while the minimum deformation is 0 mm at the fixed support. The deformation pattern confirms bending behavior due to applied loading conditions.

3.2 Curved Beam with Radius(R) = 0.5 m

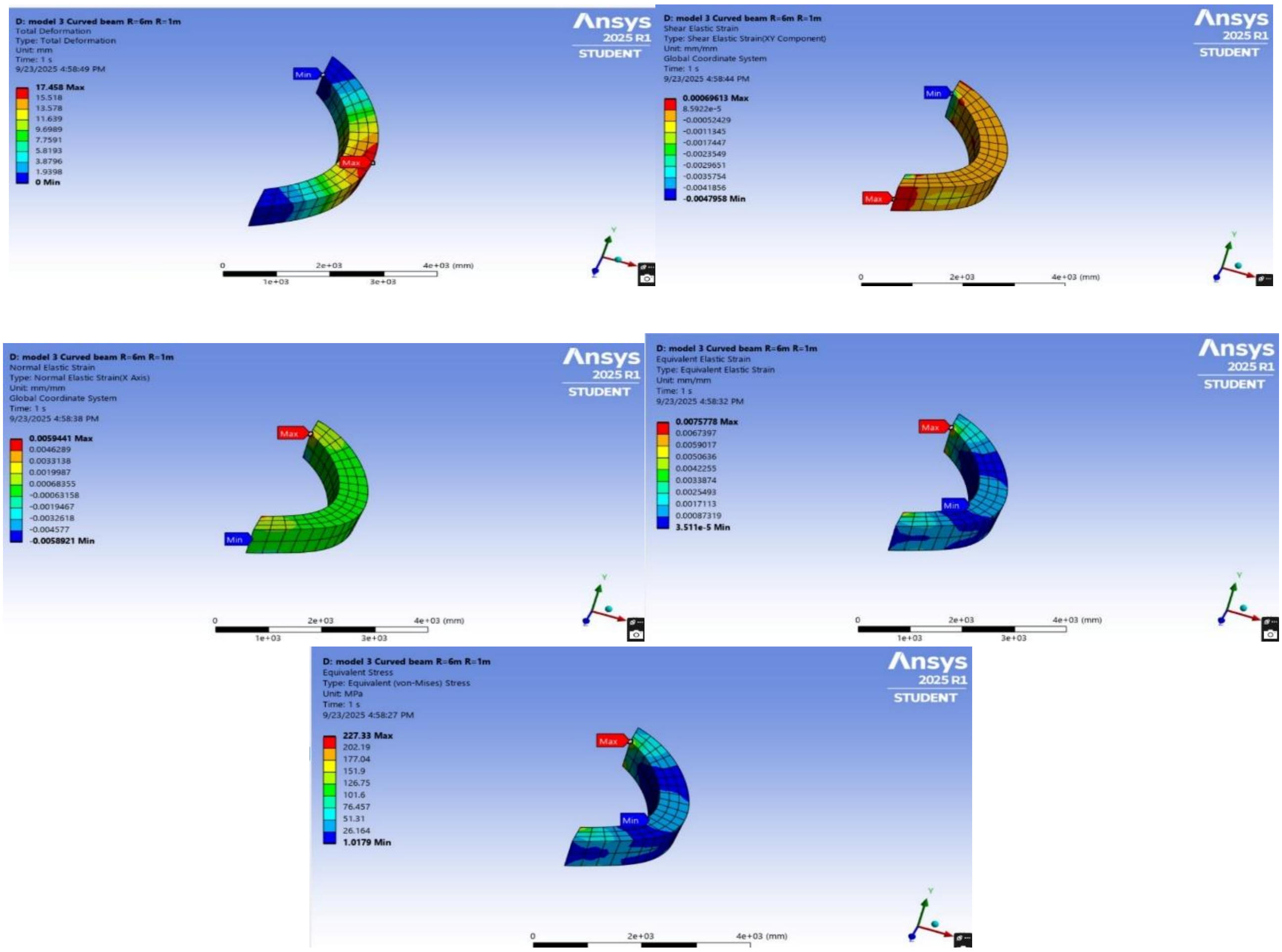
Figure 3.2 Analysis in Ansys of Curved Beam with Radius R = 0.5m



- The beam has two fixed supports at points A and C, and a pressure of 2 MPa is applied at point B. This setup simulates structural response under static loading conditions.
- The maximum stress value is 164.16 MPa observed near the loaded region, while the minimum stress is 0.91793 MPa. The stress concentration is highest at the pressure application point.
- The maximum strain is 0.0054719 mm/mm observed near the loaded section, while the minimum strain is 7.8615e-5 mm/mm. The strain concentration is highest in regions under maximum bending stress.
- The maximum strain value is 0.0038646 mm/mm, while the minimum strain is -0.0037784 mm/mm. The strain distribution shows tensile effects on the outer curve and compressive effects on the inner curve.
- The maximum shear strain value is 0.00053725 mm/mm, while the minimum is -0.0035245 mm/mm. The results indicate significant shear deformation near the loaded region of the beam.
- The maximum deformation is 4.9835 mm observed near the loaded region, while the minimum deformation is 0 mm at the fixed supports. The deformation pattern indicates bending and displacement due to applied pressure.

3.3 Curved Beam with Radius(R) = 1 m

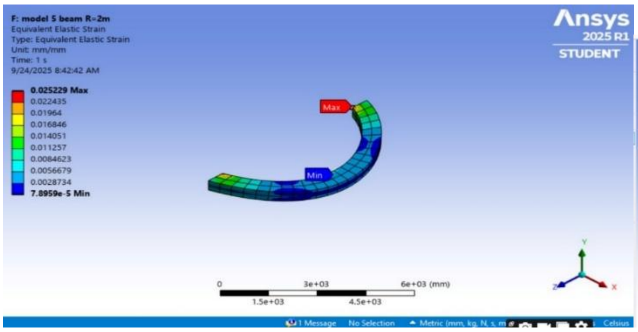
Figure 3.3 Analysis in Ansys of Curved Beam with Radius R = 1 m

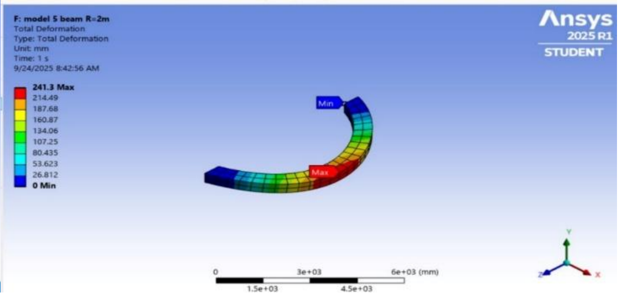


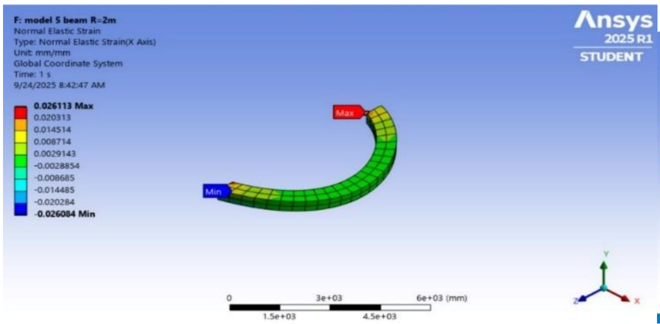
- The maximum deformation is 17.458 mm at the mid-span region, while the minimum deformation is 0 mm at the fixed supports. The deformation pattern indicates significant bending under applied loading.
- The maximum shear strain is 0.00069613 mm/mm, while the minimum is -0.0047958 mm/mm. The strain concentration occurs near the loaded and support regions.
- The maximum strain value is 0.0059441 mm/mm, while the minimum is -0.0058921 mm/mm. The outer region experiences tension, whereas the inner region undergoes compression.
- The maximum equivalent strain observed is 0.0075778 mm/mm, and the minimum value is 3.511e-5 mm/mm. Higher strain is concentrated at the outer curved surface, while lower strain appears near the inner region.
- The beam is fixed at end A and subjected to a uniform pressure load of 2 MPa at surface B. The setup aims to evaluate deformation and stress response under applied loading conditions.

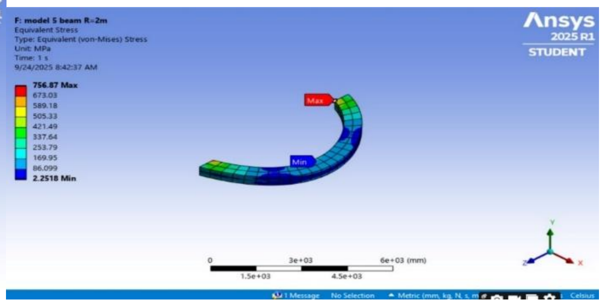
3.4 Curved Beam with Radius(R) = 2 m

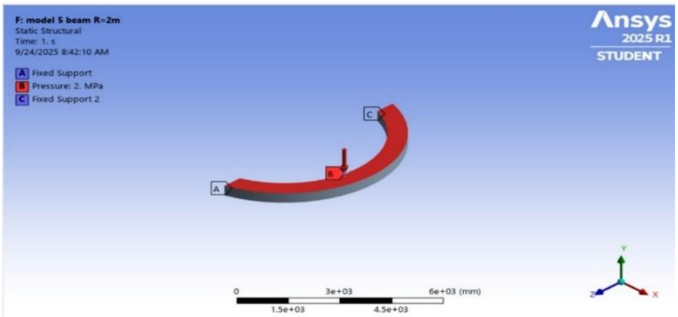
Figure 3.4 Analysis in Ansys of Curved Beam with Radius R = 2 m









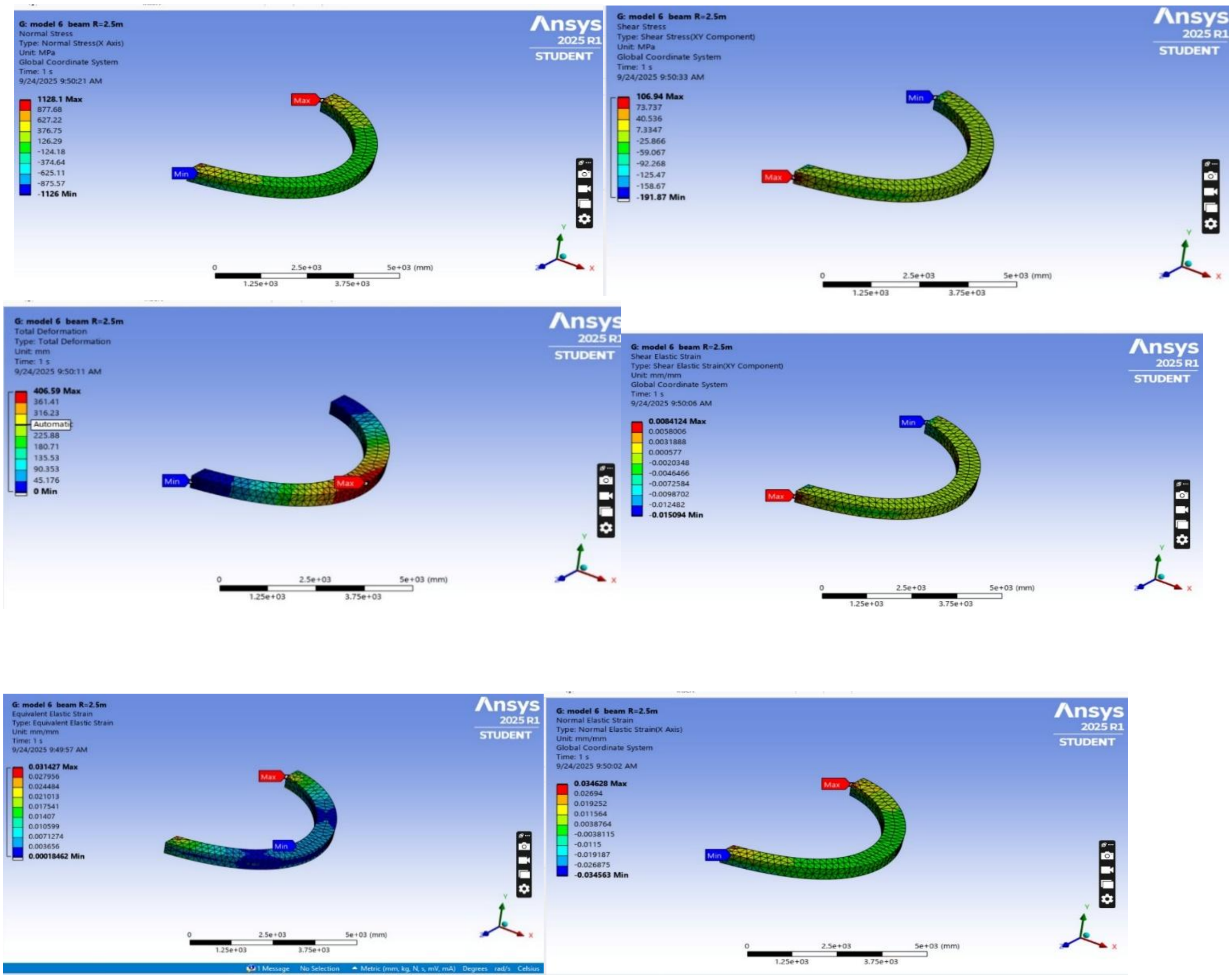


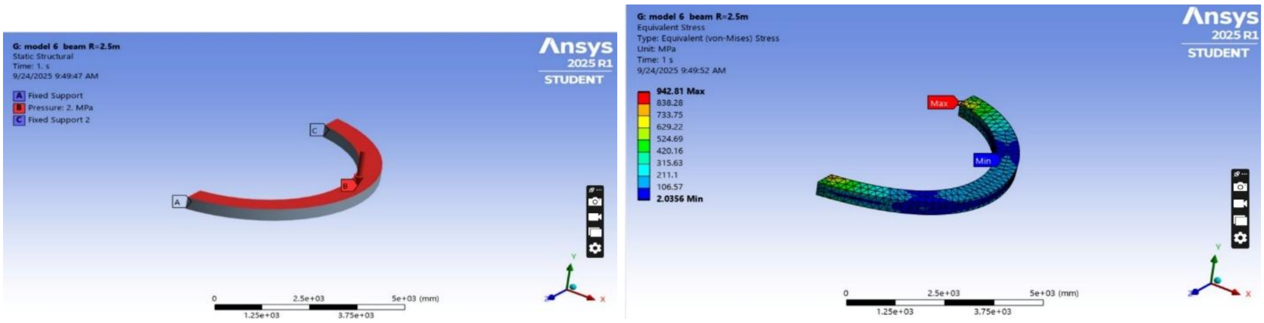
- The maximum deformation observed is 241.3 mm, while the minimum deformation is 0 mm at the fixed support. The deformation distribution increases smoothly along the curvature, showing greater displacement near the loaded end due to bending and applied external pressure.
- The maximum shear strain value is 0.0053621 mm/mm, while the minimum is -0.01141 mm/mm. The strain concentration is observed near the loaded region, indicating higher shear deformation along the beam curvature and lower values toward the fixed support.
- The maximum normal strain is 0.026113 mm/mm, and the minimum is -0.026084 mm/mm. The peak strain appears near the loaded section, while compressive strain is concentrated at the opposite end, showing tension-compression behavior along the beam curvature.
- The maximum equivalent strain recorded is 0.025229 mm/mm, while the minimum value is 7.8959e-5 mm/mm. The highest strain occurs at the loaded end, indicating localized deformation, whereas the lower strain regions are observed near the fixed or less stressed portions.
- The maximum stress recorded is 756.87 MPa, while the minimum stress is 2.2518 MPa. The highest stress concentration occurs near the loaded end, indicating critical regions under bending, whereas the minimum stress appears in the less deformed mid-portion of the beam.

- Fixed supports are applied at points A and C, while a uniform pressure of 2 MPa is applied downward at point B. This configuration represents a static structural analysis under combined boundary constraints and applied pressure load.

3.5 Curved Beam with Radius(R) = 2.5 m

Figure 3.5 Analysis in Ansys of Curved Beam with Radius R = 2.5 m

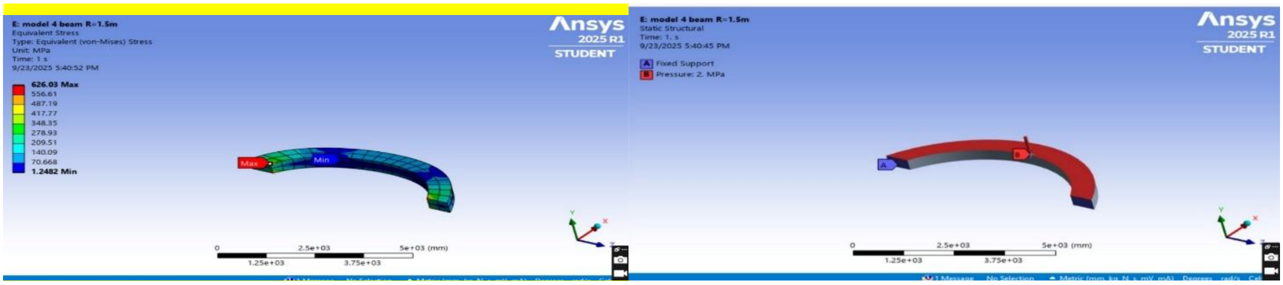


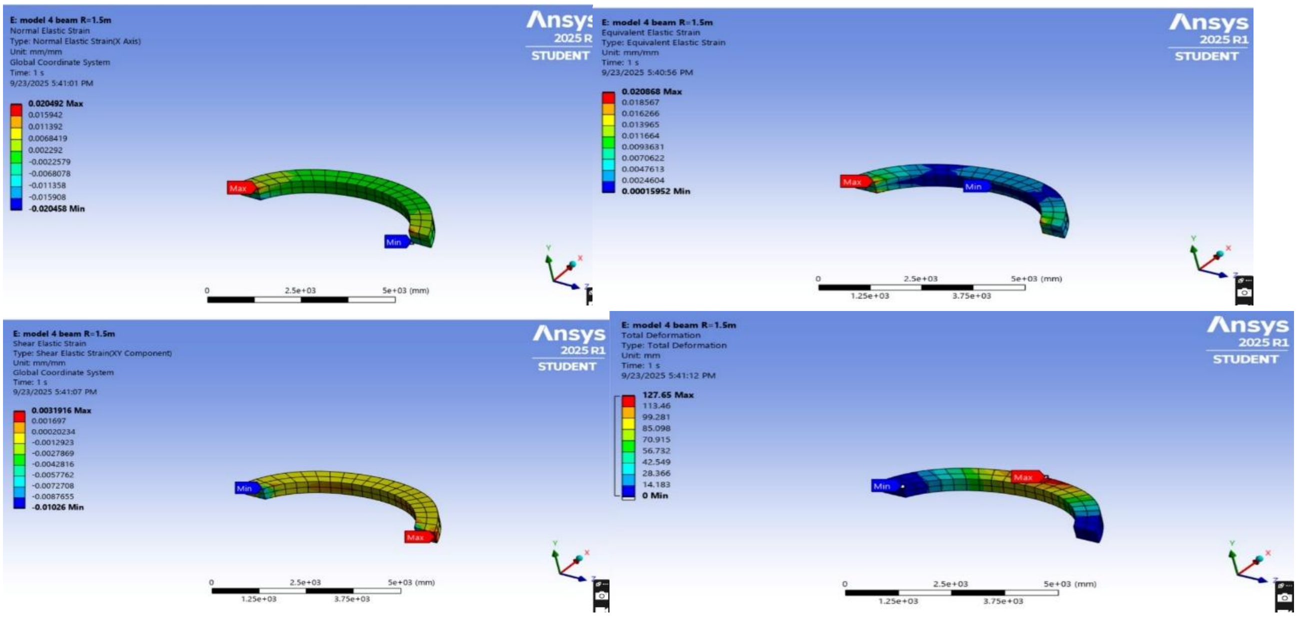


- The maximum shear stress observed is 106.94 MPa, while the minimum value is -191.87 MPa. The red zone indicates the region of maximum shear stress, and the blue zone denotes the minimum shear stress region.
- The maximum normal stress recorded is 1128.1 MPa, while the minimum stress value is -1126 MPa. The red region represents the tensile stress zone, and the blue region indicates the compressive stress zone in the beam.
- The maximum deformation observed is 406.59 mm, while the minimum deformation is 0 mm. The deformation increases progressively from the fixed end toward the free end, indicating maximum displacement near the loaded region and minimal displacement at the supports.
- The maximum shear elastic strain is 0.0084124 mm/mm, and the minimum is -0.015094 mm/mm. The strain concentration is highest near the loaded end and decreases toward the fixed support, indicating localized deformation under applied shear stress.
- The maximum strain is 0.034628 mm/mm, while the minimum strain is -0.034563 mm/mm. The highest strain concentration occurs near the loaded end, indicating tension, while compression is observed at the opposite end, showing typical bending behavior of the curved beam.
- The maximum strain value recorded is 0.031427 mm/mm, while the minimum strain is 0.00018462 mm/mm. The strain concentration is highest near the loaded curved edge, indicating significant deformation due to bending, while the lower region experiences minimal strain.
- The maximum stress observed is 942.81 MPa, while the minimum stress is 2.0356 MPa. The highest stress concentration occurs near the loaded curved edge, indicating a critical zone of bending, whereas the opposite side experiences significantly lower stress levels.

3.6 Curved Beam with Radius(R) = 1.5 m

Figure 3.6 Analysis in Ansys of Curved Beam with Radius R = 1.5 m

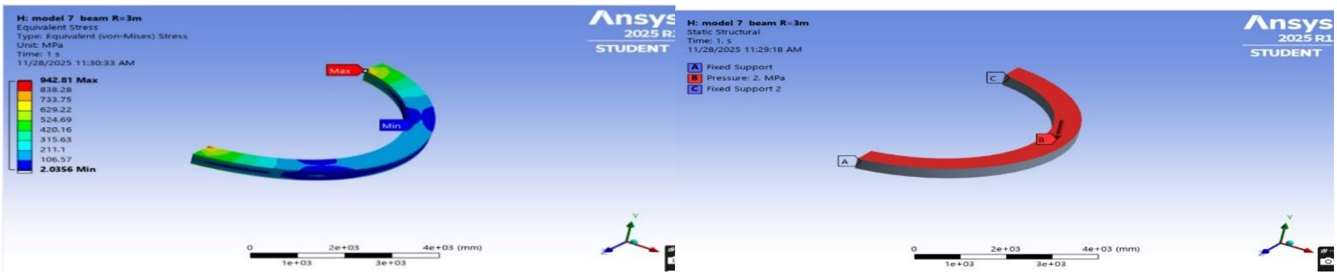


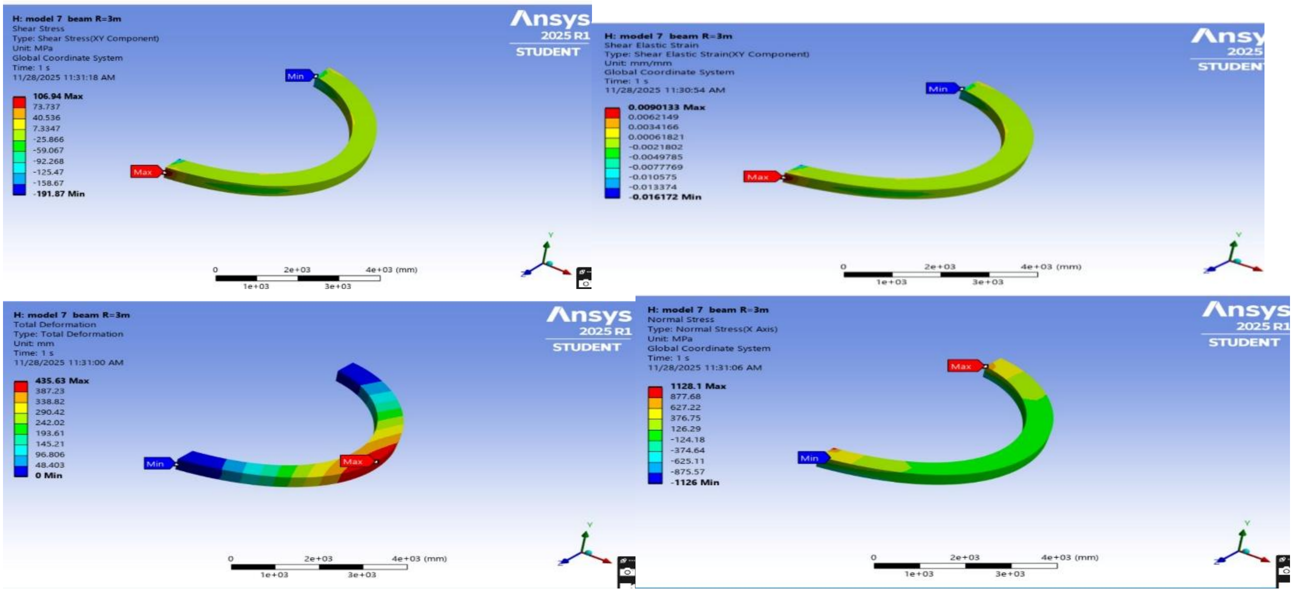


- The maximum stress observed is 626.03 MPa at the fixed end, while the minimum stress is 1.2482 MPa near the free edge. The stress concentration occurs prominently at the restrained region.
- The maximum strain value obtained is 0.020868 mm/mm at the fixed end, while the minimum strain value is 0.00015952 mm/mm near the free edge, showing higher deformation concentration around the load application region.
- The maximum strain observed is 0.020492 mm/mm at the inner curved section, while the minimum strain is -0.020458 mm/mm at the outer edge, indicating tension and compression zones developed due to applied loading and boundary conditions.
- The maximum shear strain obtained is 0.0031916 mm/mm at the outer curved region, while the minimum value is -0.01026 mm/mm near the fixed end, indicating significant shear deformation due to applied pressure and geometric curvature.
- The maximum deformation is 127.65 mm at the free end, while the minimum is 0 mm at the fixed support. The deformation gradually increases along the curvature, indicating higher displacement at the loaded region due to applied pressure.

3.7 Curved Beam with Radius(R) = 3 m

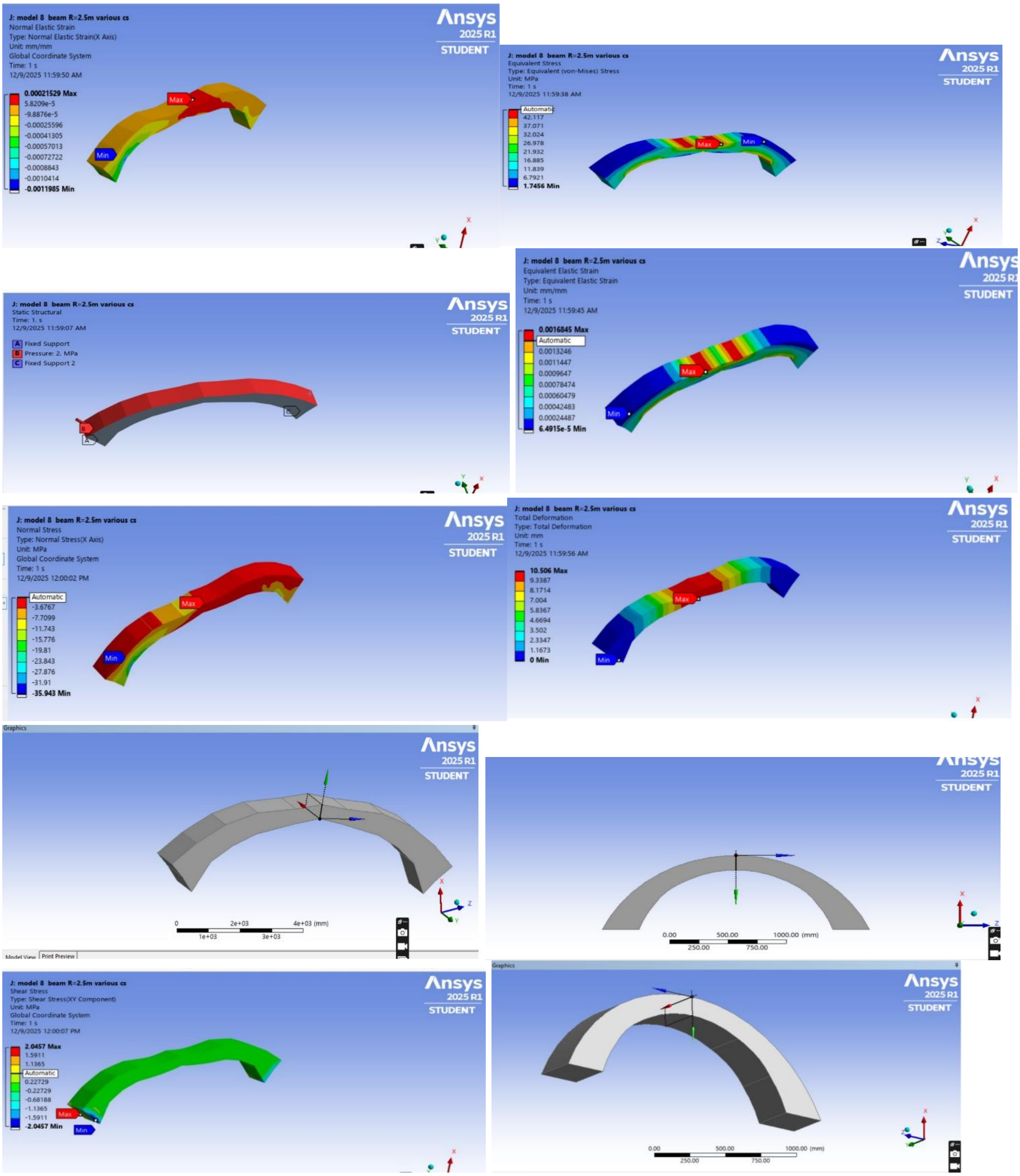
Figure 3.7 Analysis in Ansys of Curved Beam with Radius R = 3 m





- The minimum stress of 2.0356 MPa occurs near the opposite end, where loading influence is minimal. The gradient confirms that bending and curvature effects dominate the stress pattern in the beam.
- The minimum strain of –0.016172 mm/mm is observed at the opposite curved end, reflecting strain reversal due to bending and torsional effects. The overall contour confirms non-uniform shear behavior along the curved geometry.
- The maximum shear stress of 106.94 MPa occurs near the loaded end of the curved beam, showing the primary region of shear concentration. The minimum stress reaches –191.87 MPa at the opposite end, indicating reverse shear due to bending and torsional action. The distribution highlights the asymmetric shear behavior induced by the curved geometry and applied loading.
- The curved beam records a maximum normal stress of 1128.1 MPa at the loaded end, marking the critical tension/compression zone due to bending. The minimum stress reaches –1126 MPa near the opposite end, indicating significant compressive stress reversal. The stress pattern confirms dominant bending action influenced by the beam's curvature.
- The curved beam exhibits a maximum total deformation of 435.63 mm near the free or highly loaded end, indicating the zone of greatest displacement. The minimum deformation is 0 mm at the fixed/support region, confirming appropriate boundary conditions. The deformation pattern shows increasing displacement along the curvature due to bending dominance.
- The figure displays the normal elastic strain distribution along the beam, with the maximum strain of 0.0371 mm/mm at the red point and the minimum strain of -0.0370 mm/mm at the blue point. The strain varies between -0.0288 mm/mm and 0.0289 mm/mm, indicating localized deformation along the beam under the applied load.

3.7 Curved Beam with varying cross section Radius(R) = 2.5 m



- The image shows a 2.5m long beam subjected to a uniform pressure of 2 MPa. Fixed supports are applied at both ends of the beam (labeled A and C). The beam's deflection under this load is visible, indicating how it bends under the applied pressure. The analysis is performed using ANSYS software for static structural analysis.
- The maximum stress is 42.117 MPa, located at the outermost points of the beam, while the minimum stress is 1.7456 MPa, seen at the beam's fixed supports. The color gradient represents the stress values, with red indicating high stress and blue indicating low stress.

- The maximum strain is 0.0016845 mm/mm, occurring at the outermost part of the beam, while the minimum strain is 6.4915e-5 mm/mm, observed at the fixed supports. The color gradient illustrates the strain levels, with red indicating high strain and blue indicating low strain.
- The maximum strain is 0.00021529 mm/mm, located at the beam's top surface, while the minimum strain is -0.0011985 mm/mm, occurring at the bottom surface. The strain distribution is shown through a color gradient, with red representing the highest strain and blue indicating the lowest.
- The total deformation in a 2.5m beam subjected to a load, with the deformation values ranging from 0 mm to 10.506 mm. The maximum deformation of 10.506 mm occurs at the center of the beam, while the minimum deformation is 0 mm at the fixed supports. The color gradient indicates the level of deformation, with red showing the highest deformation and blue showing the lowest.
- The maximum stress is -3.6767 MPa, located at the top of the beam, while the minimum stress is -35.943 MPa, occurring at the bottom. The color gradient represents stress levels, with red indicating the highest compressive stress and blue showing the lowest stress.
- The maximum shear stress is 2.0457 MPa, occurring at the beam's lower end, while the minimum shear stress is -2.0457 MPa, located at the opposite end. The color gradient indicates the shear stress levels, with red showing the highest positive stress and blue indicating the lowest negative stress.

4. Comparative Analysis

Table No.4.1 Comparison of Maximum Values

Analysis Type	Equivalent von-Mises Stress (MPa)	Equivalent Elastic Strain (mm/mm)	Normal Elastic Strain (mm/mm)	Shear Elastic Strain (mm/mm)	Total Deformation (mm)
FLAT BEAM	131.26	0.00438	0.00058	0.0007	22.638
R = 0.5m	164.16	0.00547	0.00387	0.00537	4.9835
R = 1m	227.33	0.00758	0.00594	0.00069	17.458
R = 1.5m	626.03	0.03087	0.02049	0.00319	127.65
R = 2m	756.87	0.02523	0.03463	0.00841	241.3
R = 2.5m	942.81	0.03143	0.02611	0.00536	406.59
R = 3m	942.81	0.03333	0.03713	0.00901	435.63

Table No.4.1 Comparison of Minimum Values

Analysis Type	Equivalent von-Mises Stress (MPa)	Equivalent Elastic Strain (mm/mm)	Normal Elastic Strain (mm/mm)	Shear Elastic Strain (mm/mm)	Total Deformation (mm)
FLAT BEAM	0.92481	3.1819E	-0.0007207	-0.0006207	0
R = 0.5	0.91793	7.8615E	-0.0037784	-0.0035245	0
R = 1m	1.079	3.51E-05	-0.00592	-0.0048	0
R = 1.5m	1.2482	0.0001595	-0.020458	-0.01026	0
R = 2m	2.2518	7.8959E	-0.026084	-0.01141	0
R = 2.5m	2.0356	0.00018462	-0.034563	-0.015094	0
R = 3m	2.0356	0.00016	0.037032	-0.01026	0

5. Conclusion

This study provides a comprehensive comparative analysis of beams curved in plan with varying cross-sections, focusing on the influence of different beam radii on stress, strain, and deformation behaviors under static loading conditions. The results clearly indicate that beam curvature has a significant impact on its structural performance. As the radius of curvature decreases, the beam experiences more concentrated stress, particularly at the ends, and higher deformation at the mid-span. Specifically, beams with smaller radii (R = 1m and R = 2m) exhibit significantly higher von-Mises stresses (up to 942.81 MPa for R = 2.5m) and equivalent elastic strains (up to 0.031427 mm/mm for R = 2.5m), compared to the flat beam configuration (R = 6m). This suggests that beams with smaller radii are more prone to localized stress concentrations and deformation under similar loading conditions, which can lead to premature material failure if not appropriately reinforced.

The analysis of normal elastic strain distribution further highlights the bending behavior of these beams, where tension occurs at the top and compression at the bottom, with significant strain at the ends for beams with smaller radii. Additionally, the shear strain distribution underscores how bending affects internal forces, with shear strain concentrations appearing at the ends and increasing as the curvature tightens. Deformation patterns confirm the impact of curvature, with larger deformations observed at the mid-span of more curved beams, reaching up to 406.59 mm for R = 2.5m.

These findings underscore the critical role of curvature, beam geometry, and cross-sectional variation in determining the overall structural integrity and performance of beams. The results emphasize the necessity of carefully considering beam curvature in design, as smaller radii lead to higher stresses and deformations. Consequently, appropriate design measures, such as material selection, reinforcement, and safety factors, must be incorporated to ensure structural stability and prevent failure in beams with tighter curvatures. This comprehensive analysis highlights the importance of optimizing beam design for both performance and safety in real-world applications.

6. References

1. Elgaili Mukhtar, M. (2022). *Behavior and collapse analysis of horizontally curved beams under vertical loads: Comparison with ETABS simulations. International Journal of Civil Engineering and Technology, 13*(2), 101–112. https://doi.org/10.1016/ijcivtech.2022.13.2.101

2. Erkmen, R. E., & Bradford, M. A. (2009). *Nonlinear elastic analysis of composite beams curved in-plan. Engineering Structures, 31*(7), 1613–1624. https://doi.org/10.1016/j.engstruct.2009.02.008
3. Ghuku, S., & Saha, K. N. (2017). *Large deflection behaviour of curved beams under static loading: A review. International Journal of Mechanical and Civil Engineering, 11*(3), 45–58. https://doi.org/10.1016/ijmce.2017.11.3.045
4. Hansora, A. G., & Patel, H. S. (2024). *Analysis of spatial curved bi-fixed beam with varying curvature and cross-sectional area using finite displacement transfer method. International Journal of Emerging Trends in Engineering Research, 12*(4), 39–48. https://doi.org/10.30534/ijeter/2024/011242024
5. Kumar, M. (2021). *Parametric study on box-girder bridges with varying curvature using SAP2000 under IRC Class A moving loads. Journal of Bridge Engineering and Structures, 18*(4), 201–212. https://doi.org/10.1061/jbes.2021.18.4.201