Finite Element Analysis of the Buckling Behavior of Laminated Carbon Fiber-Reinforced Plastic (CFRP) and Glass Fiber-Reinforced Polymer (GFRP) Rectangular Beams

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***Abstract*—This study examines the buckling behavior of rectangular carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) beams using finite element analysis (FEA) in ANSYS. Composite materials are widely used in engineering applications due to their superior strength-to-weight ratio and customizable mechanical properties. The beam is modeled with multiple layers, incorporating various fiber orientations to assess their impact on buckling resistance. The analysis is performed under axial compressive loading, determining the critical buckling loads. The results emphasize the influence of material properties, boundary conditions, and geometric configurations on buckling performance. This research provides valuable insights for optimizing composite beam design to enhance structural stability.**

***Index Terms*—Finite Element Analysis, Buckling, Carbon fiber-reinforced polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), Rectangular beam, ANSYS, Critical Load, Structural Stability.**

I. INTRODUCTION

Finite Element Analysis (FEA) plays a crucial role in understanding the buckling behavior of laminated composite beams, which are widely used in lightweight structural applications such as aerospace, civil engineering, and automotive components. Unlike isotropic materials, the buckling response of laminated composite beams is significantly influenced by their anisotropic nature and the stacking sequence of layers.

Extensive research has been conducted on the buckling behavior of laminated composite beams using various analytical and numerical methods. Reddy [1] provided analytical and numerical solutions for bending, buckling, and free vibration problems of laminated composite plates and beams by incorporating different lamination theories. Several other studies have focused on analytical approaches to address this complex behavior. Khdeir and Reddy [2] employed the state-space approach to examine the buckling of cross-ply laminated beams under various end conditions. Song and Waas [3] utilized a higher-order theory with a cubic displacement variation through the thickness to analyze buckling and free vibration in stepped laminated beams. A discrete layer theory-based model for bending, buckling, and vibration of thin and thick beams was introduced by Karama et al. [4]. Matsunaga [5], using power series expansion, developed a one-dimensional (1D) higher-order theory for laminated beams under axial stress, deriving fundamental dynamic equations and numerical results for buckling stresses, natural frequencies, and interlaminar stresses. Dafedar and Desai [6] formulated a unified mixed higher-order analytical method for laminated composite struts, enabling the calculation of both overall buckling and wrinkling loads in multilayered, multi-core sandwich struts. Kapuria et al. [7] assessed a zigzag 1D laminated beam theory, comparing analytical solutions with exact 2D elasticity solutions for different loading conditions, frequencies, and axial buckling. Boay and Wee [8] developed a closed-form expression by integrating Euler-Bernoulli beam theory with classical laminate theory (CLT) to predict the bending, buckling, and vibration behavior of laminated beams with various end conditions. Zhen and Wanji [9] analyzed vibration and stability problems in laminated composite and soft-core sandwich beams using multiple displacement-based theories. Further advancements include Fridman and Abramovich's [10] study on laminated composite beams reinforced with piezoelectric layers under axial compression, where they applied first-order shear deformation theory (FSDT) along with linear piezoelectric constitutive relations. Emam and Nayfeh [11] explored post-buckling behavior using a closed-form solution, analyzing how different lay-up configurations influence the static and dynamic responses. Gupta et al. [12] introduced accurate closed-form expressions for post-buckling behavior in axially immovable composite beams, employing the Rayleigh-Ritz method. In more recent work, Li and Qiao [13] investigated the buckling and post-buckling response of shear-deformable anisotropic laminated beams with initial imperfections under axial compression. On the numerical front, various computational techniques have been employed to study laminated composite beams. Moradi and Taheri [14] applied the differential quadrature method for buckling analysis of general laminated composite beams. This study utilizes ANSYS to simulate and analyze the stress and strain distribution in a rectangular laminated composite beam. The primary focus is on Von Mises stress, which is crucial for evaluating failure criteria in ductile materials.

II. METHODOLOGY

2.1 A rectangular beam with dimensions L = 1 m, B = 0.1 m, and H = 0.02 m is designed using a composite shell structure in ANSYS considered for the analysis. The model was defined with multiple layers, each composed of Carbon Fiber-Reinforced Polymer (CFRP) and Glass Fiber-Reinforced Polymer (GFRP) materials. The material orientations were set at 90°, 0°, 90°, and 0°, with a uniform thickness of 0.01 units per layer. The shell layup configuration was specified using the Shell Section tool, ensuring that each layer was properly assigned to maintain a uniform composition. The fiber orientation (Theta) alternated between 90° and 0°, forming a cross-ply laminate configuration. This configuration enhances structural stiffness and strength. Figure. 1 shows a multilayered beam consisting of N-stacked layers under axial compression. Each lamina has its own thickness and material property. The effect of shear is considered by the first-order shear deformation theory (FSDT), or in other words, Timoshenko beam theory for the 1D case [1].

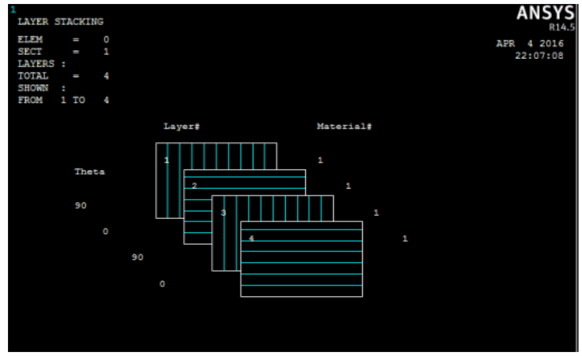

Figure 1. Layer stacking for a CFRP and GFRP material with four layers

2.2 Meshing and Boundary Conditions: A structured meshing technique was employed to ensure accuracy in the numerical results. The model was constrained at one end while subjected to an external mechanical load at the opposite end. Also, applied loading conditions, which are typically uniform or point loads that cause buckling. For a buckling analysis, a linear elastic buckling analysis is typically performed to determine the critical buckling load. Figure 2. shows the selected area, which can be meshed and analyzed. Engineers use such definitions to model plates, shells, or other structural components in FEA simulations.

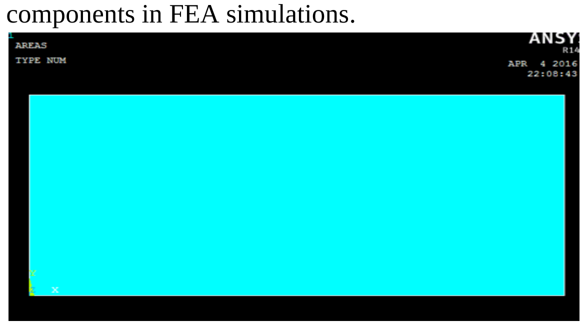

Figure 2. The selected area, which can be meshed and analyzed

2.3 The ANSYS solver was used to compute the nodal solutions, including von-Mises stress and strain distributions. The analysis was performed under static loading conditions, and contour plots were generated for result visualization. The figure represents a nodal displacement contour plot of a rectangular plate analyzed, the deformation pattern and critical displacement areas are visualized, which can be used for further structural assessment and optimization. The displacement range is shown on a scale, with blue indicating minimal displacement and red representing the highest displacement (0.007658 units). The maximum displacement (DMX = 0.007658) and SMX (same value) suggest that deformation is concentrated in a particular region. The mesh grid consists of quadrilateral elements, and the symmetric pattern hints at a centrally applied force or pressure.

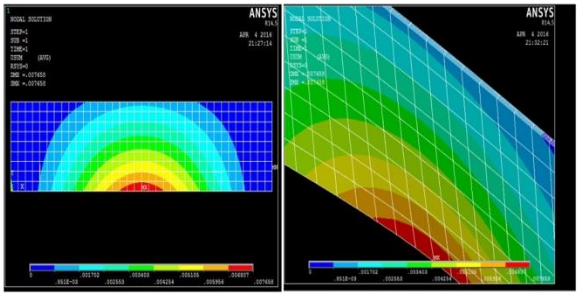

Figure 3. Nodal displacements of a rectangular plate

The figure 3. represents a nodal displacement contour plot of a rectangular plate analyzed**,** the deformation pattern and critical displacement areas are visualized, which can be used for further structural assessment and optimization. The displacement range is shown on a scale, with blue indicating minimal displacement and red representing the highest displacement (0.007658 units). The maximum displacement (DMX = 0.007658) and SMX (same value**)** suggest that deformation is concentrated in a particular region. The mesh grid consists of quadrilateral elements, and the symmetric pattern hints at a centrally applied force or pressure.

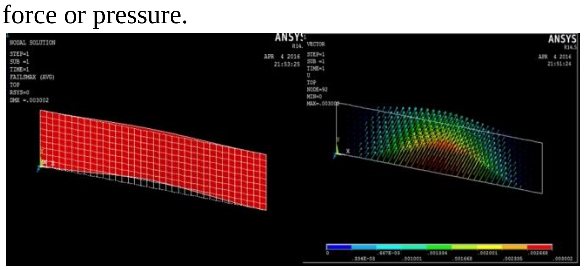

Figure 4**.** The deformed shape of the plate of a rectangular plate under load

The figure 4. Illustrates the deformed shape of the plate, where the maximum displacement (DMX) is 0.03002 units. The deformation follows an expected pattern, with higher displacements observed at the free end, while the constrained edge remains stationary. This confirms the correct application of boundary conditions, simulating a cantilevered plate.

III. RESULTS AND DISCUSSION

3.1 The von-Mises stress results highlight the regions of maximum stress concentration, particularly near the fixed boundary and load application points. The maximum stress (DMX) observed was 0.00302, indicating the most critical area in the structure. The von-Mises stress contour plot indicates that the stress ranges from 22,333.5 to 4.97×10^{7} units. The highest stress concentration appears in the fixed region, a critical location for potential failure. The stress distribution is symmetric, and stress values remain within expected limits, ensuring structural integrity under applied loads. This analysis helps in evaluating material strength and failure risk under static loading conditions. The color legend at the bottom provides a stress scale for interpretation.

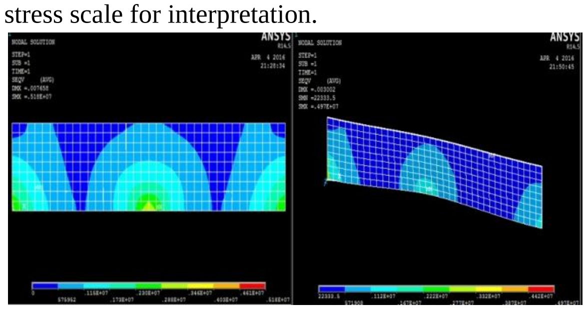

Figure 5. Von-Mises stress distribution for a rectangular plate under load

3.2 Mechanical Strain Analysis Strain distribution results demonstrate deformation patterns across the plate, with higher strain observed near the load application zone. The minimum strain (SMN) and maximum strain (SMX) were recorded as 5.568E-06 and 4.415E-04, respectively. The strain analysis shows minimum and maximum values ranging from 5.568E-06 to 4.15E-04. The strain is highest at the constrained section, where bending effects dominate. The lower values near the free end indicate minimal stretching. The left side is constrained, indicating a cantilevered boundary condition. This analysis helps in evaluating material deformation behavior under static loading and identifying potential failure zones. The results highlight the expected bending behavior of a cantilevered plate under 1.2 KN applied load. The stress concentration near the fixed support suggests a potential failure zone, emphasizing the need for material reinforcement or shape optimization in real-world applications. The strain distribution follows stress trends, confirming the validity of the results. The maximum stress values should be compared with the material's yield strength to determine failure risks.

Overall, the study successfully evaluates the mechanical response of the plate under static loading conditions. Further optimization, such as material selection and geometric modifications, can enhance structural performance.

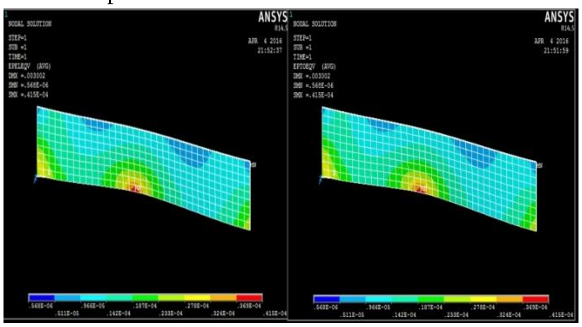

Figure 6**.** Equivalent von-Mises strain distribution for a rectangular plate under load

IV. CONCLUSION

The finite element analysis (FEA) of a rectangular plate under static loading using ANSYS provided valuable insights into its deformation, stress, and strain behavior. The maximum displacement of 0.03002 units confirms the expected bending pattern, with higher deflections at the free end and minimal movement at the constrained edge. The von-Mises stress distribution identified peak stress zones near the fixed support, indicating potential failure regions. Similarly, the strain distribution followed the stress pattern, highlighting the plate's deformation characteristics. These results emphasize the importance of stress concentration analysis in structural design. To improve performance and prevent failure, further optimization, such as material selection, reinforcement, or geometric modifications, should be considered.

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