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SIMULATION OF THE INFLUENCE OF FIBER VOLUME FRACTION AND FIBER ORIENTATION ON THE STRENGTH OF POLYESTER COMPOSITE REINFORCED WITH GLASS FIBER IN BENDING STRENGTH

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Abstract. Fiber-reinforced composites can be classified into two parts, namely short fiber composites and long fiber composites. Long fibers are generally stronger than short fibers. Long fiber (continuous fiber) is more efficient in laying than short fiber but short fiber is easier to lay than long fiber. Fiber length affects the processability of the fiber composite. Judging from the theory, long fibers can transfer the load and stress from the stress point to the other fiber. In this research, we simulated the effects of volume fraction and fiber orientation in glass fiber-reinforced polyester composites on bending strength to examine the effect of each parameter on the mechanical properties of glass fiber composites. The mechanical properties of the composite were tested using the three-point bending and tensile testing methods. The study expects to find variations in mechanical properties with changes in the glass fiber volume fraction and fiber orientation. In this study, it is planned to function in a relevant environment, the components in this study must be able to operate properly and have been well integrated with prototype manufacturing that has been tested as a test tool function. Notably, the pinnacle of the bending test, measuring 170.41 MPa, was achieved at the specific combination of a 0.5 Fiber Volume Fraction and the 0-90^{o} fiber orientation.
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Keywords : Volume Fraction, Composite, Fiberglass, Simulation, Three-point Bending

1. INTRODUCTION

Composite is a material that consists of two or more different types of materials combined together to create desired properties that may not be achievable by each individual material separately. When combined, these materials form a new system that often has superior characteristics compared to the individual materials that constitute it. Composites are commonly used in various applications such as the automotive industry, aviation, construction, and others, to combine the strength and other properties of various materials into a stronger or more resilient system against various loads or conditions [1].

Composites exhibit a range of mechanical properties depending on the specific materials utilized and their arrangement within the composite structure [2] [3]. High strength, characteristic of composites, refers to their capacity to endure stress without deformation or fracture. Similarly, their high stiffness makes them resistant to deformation under external forces, maintaining structural integrity and dimensional stability [4]. Designed for toughness, composites can absorb energy and deform before fracturing, offering notable impact resistance and averting catastrophic failure. Moreover, their exceptional fatigue resistance enables them to endure cyclic loading without developing cracks or failures over time. With engineered resistance to creep, composites can withstand long-term exposure to mechanical stress, ensuring prolonged structural stability and durability. Notably, their low density and lightweight nature, in contrast to conventional materials like metals, render composites advantageous in weight-sensitive applications, particularly in aerospace, automotive, marine, and construction industries. Understanding these mechanical properties is essential for the efficient design, engineering, and selection of composite materials tailored to various industrial applications.

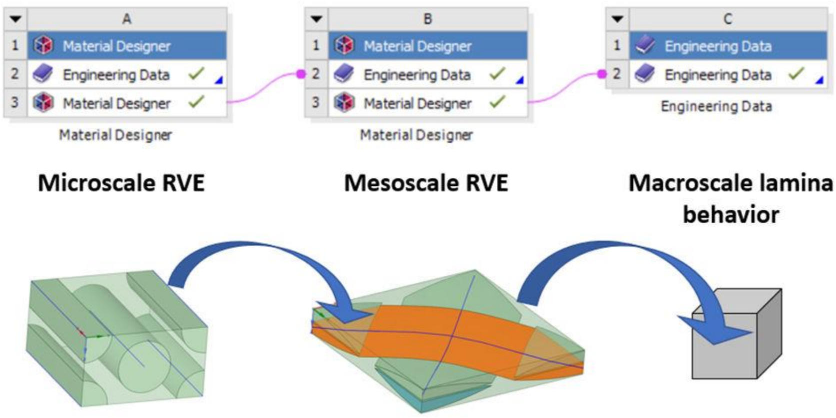

Figure 1. Material designer in simulation process

In composite materials analysis, Representative Volume Elements (RVEs) at different scales characterize material properties. The microscale RVE captures detailed microstructural features such as fibers and the matrix, determining effective properties like stiffness and strength from these interactions, considering fiber arrangement, orientation, and fiber-matrix interfaces. The mesoscale RVE averages these microstructural details into a more homogenized form while retaining some features, bridging the gap between microscale details and macroscale behavior. It considers phenomena like fiber bundles, local variations in fiber volume fraction, and defects, helping to understand the overall mechanical behavior of the composite without detailed modeling of every interaction. At the macroscale, the composite is treated as a continuum with averaged properties derived from microscale or mesoscale analyses, focusing on the behavior of composite laminates under various loading conditions. This scale is used for structural analysis and design, using homogenized properties for effective stiffness, strength, and thermal properties of the composite lamina. Each scale—microscale, mesoscale, and macroscale—provides essential insights for accurately predicting and designing composite materials.

Composite simulation refers to the process of using software or mathematical methods to predict and understand the behavior of composites under various conditions. Such simulations may involve microstructural analysis, the distribution of matrix and fibers, as well as the influence of the environment on the composite performance. The goal of composite simulation is to understand how factors such as fiber volume fraction, fiber orientation, matrix used, and environmental conditions can affect the mechanical and physical properties of the composite material. By utilizing simulations, engineers can optimize composite designs for specific applications, estimate the material's lifespan, and analyze the composite's response to different mechanical loads [5]. Composite simulation is crucial in saving costs and time during the product development process, as it allows for careful evaluation before physical production takes place [6].

Mohammad Alfian Ilmy et al. (2018) conducted research on the Influence of Glass Fiber Volume Fraction on the Mechanical Properties of Glass Fiber/Epoxy Composites Using the Variation Method. The findings from the conducted research revealed that increasing the vacuum pressure enhanced the mechanical properties of the glass fiber mat 300/epoxy AB777 composite. The highest tensile strength of the composite, reinforced with glass fiber mat 300 and epoxy matrix AB777, was observed at a 50% fiber volume fraction with a pressure of 0.5 bar, measuring 138.18 MPa, while the lowest was exhibited by the 30% volume fraction at 0.2 bar, measuring 96.60 MPa. Tensile strength increased with the increment of the fiber volume fraction. The highest impact resistance of the fiberglass mat 300/epoxy AB777 composite was found at the optimal 45% volume fraction with a pressure of 0.5 bar, measuring 0.1913 J/mm², whereas the lowest was observed in the 30% volume fraction at 0.2 bar, measuring 0.0979 J/mm². Impact resistance began to decrease at the 50% fiber volume fraction.

Alamsyah et al. (2020) conducted research on the Influence of Resin and Catalyst Ratio on the Tensile Strength of Fiberglass-Polyester Composites for Shipbuilding Materials. The research findings indicated that fiberglass-polyester composites with a 0.5% catalyst content exhibited a tensile strength of 4.85 kgf/mm², elongation of 2.43%, and an elastic modulus of 2.26 kgf/mm². Composites with a 1% catalyst content demonstrated a tensile strength of 5.02 kgf/mm², elongation of 1.71%, and an elastic modulus of 2.96 kgf/mm². Additionally, composites with a 1.5% catalyst content displayed a tensile strength of 5.49 kgf/mm², elongation of 1.97%, and an elastic modulus of 3.07 kgf/mm². Composites with a 2% catalyst content showed a tensile strength of 4.97

kgf/mm², elongation of 1.62%, and an elastic modulus of 3.11 kgf/mm². The tensile strength of the fiberglass-polyester composite increased from 0.5% to 1.5% catalyst content and decreased at 2% catalyst content. Moreover, the highest tensile strength for the fiberglass-polyester composite was obtained at a resin composition of 100% and a 1.5% catalyst content, with a tensile strength of 5.49 kgf/mm², elongation of 1.97%, and an elastic modulus of 3.07 kgf/mm².

This research distinguishes itself from previous studies by focusing on the detailed simulation of how fiber volume fraction and fiber orientation influence the bending strength of polyester composites reinforced with glass fibers, using ANSYS software. This study systematically examines a wider range of volume fractions, including less commonly explored ones, providing a deeper understanding of the impact of varying fiber content on bending strength and potentially identifying optimal volume fractions that balance strength and material efficiency. It also investigates a broader spectrum of fiber orientations, including off-axis angles often overlooked in earlier works, offering a thorough understanding of the anisotropic nature of composites and their bending performance under different alignments. By employing advanced ANSYS simulation techniques, including detailed finite element models that capture microstructural interactions between fibers and the matrix, the research offers new insights into composite behavior under bending loads. These simulations deliver more reliable predictions of bending strength through refined meshing techniques and enhanced material modeling, improving computational efficiency and accuracy over existing methods. Additionally, this research uniquely integrates the effects of both fiber volume fraction and fiber orientation within the same study, revealing synergistic effects and guiding more effective composite design strategies. Overall, the study advances the understanding of polyester composites with glass fibers by addressing unexplored volume fractions and orientations and utilizing innovative ANSYS simulation methods to enhance design accuracy and efficiency [2], [3], [7].

In this study, the researchers utilized ANSYS software to conduct macro-scale simulations of glass fiber composites reinforced with polyester resin. The investigation involved the deliberate variation of volume fractions, as represented by distinct layers, and the manipulation of fiber orientation. The evaluation of the mechanical properties was achieved through a comprehensive simulation process employing the three-point bending test method, which allowed for a detailed understanding of the material's structural behavior and performance under specific loading conditions.

2. METHODS

The variables utilized in this study are categorized as follows: the independent variable, the dependent variable, and the controlled variables. The independent variable, representing the volume fraction of glass fibers to polyester resin, was set at 25%, 30%, 35%, 45%, and 50%, while the fiber weave orientation was designated as (0º,90º) and (45º,135º). On the other hand, the dependent variable, specifically the maximum stress during both tensile testing and 3-point bending, was determined based on the variations of the independent variables [8]. Throughout the research, several parameters were meticulously controlled to ensure consistency and reliability. These encompassed maintaining a consistent loading speed for both tensile and bending tests, applying loading precisely at the midpoint of the specimens during bending, ensuring uniform dimensions of the test specimens in accordance with ASTM standards, and utilizing E-glass fibers for the woven fiber components.

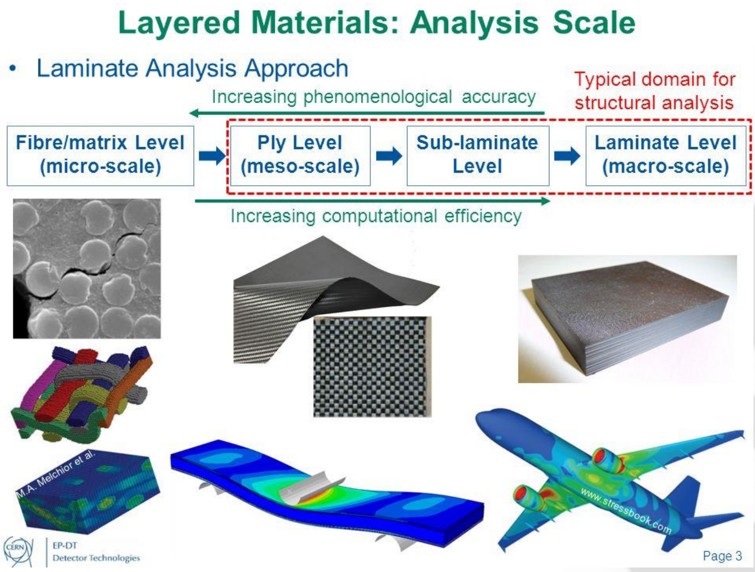

Figure 2. Simulation using ANSYS Software

Three-point bending simulation with ANSYS is a numerical method used to model and analyze the behavior of a test specimen when subjected to loading at three points of contact. This simulation provides an in-depth understanding of how the test specimen will respond under bending forces, applicable to various materials including composites and metals. The process begins with the creation of a geometric model of the test specimen, defining its dimensions and geometry to suit the research requirements [7]. Material properties such as elastic modulus and bending strength are then assigned to the specimen. Boundary conditions are set to specify the loading and support points, typically involving the application of pressure to the specimen's center with support from two contact points. ANSYS is employed to simulate the specimen's behavior, calculating its response to the bending load in terms of stress and strain. Subsequently, the results are evaluated to derive essential data such as maximum stress and strain. Furthermore, the simulation can be optimized and analyzed with variations in parameters, enabling a comprehensive understanding of how different factors influence the bending behavior. Overall, 3-point bending simulation with ANSYS serves as a valuable tool for comprehending and examining the response of test specimens under bending conditions, facilitating applications in material research and structural engineering.

The bending strength of a material is typically described by the bending stress (σ) it can withstand before it yields or breaks. The bending stress in a beam or any other structure under bending can be calculated using the bending strength equation, also known as the flexure formula. For a simple case of a beam with a rectangular cross-section experiencing a three-point bending test, the bending strength equation is:

$$\sigma = 3FL / (2bd)^2 \quad (1)$$

where:

- σ : bending stress
- F : tapplied force at the midpoint
- L : span length between the supports
- b : width of the beam
- d : depth of the beam

A meticulous and detailed series of steps are involved. First, the process commences with the precise creation of a geometric model that corresponds to the specimen under analysis. Following this, the accurate selection of appropriate materials and the determination of their mechanical properties become the subsequent crucial steps. The mesh generation also requires careful attention to ensure that the element resolution adequately represents the stress changes occurring within the test specimen during the bending process. The precise establishment of boundary conditions, including the application of loads at specific points in accordance with the 3-point bending test standards, is also a critical aspect of this modeling. Once the simulation is executed, result analysis becomes a pivotal stage in comprehending the test specimen's response to the bending load, encompassing stress, strain, and deformation that occur. The evaluation and interpretation of these simulation results allow for a profound understanding of the mechanical characteristics of the material under investigation, providing better insight into how the material will behave under bending conditions.

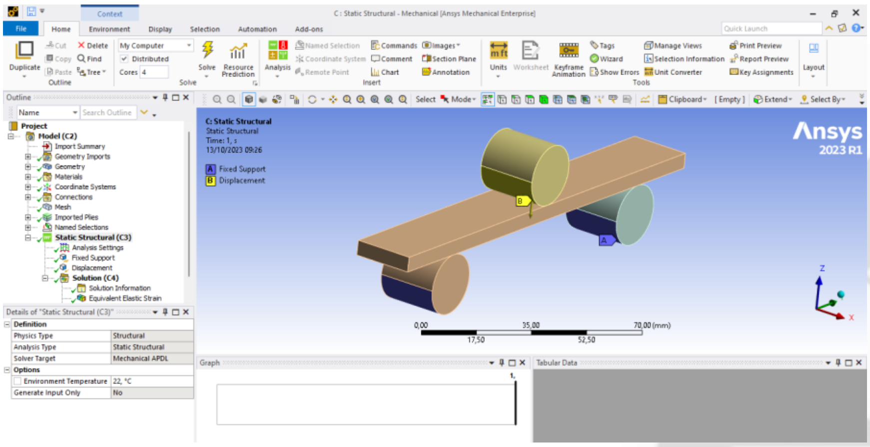

Figure 3. ANSYS Simulation Control for 3-point Bending Case using Static Structural Analysis

The parameters in the solver window for the bending test are tailored to specific configurations. The simulation model is intentionally simplified to align with the prescribed requirements of the ASTM D790 test specimen's designated observation length.

3. RESULTS AND DISCUSSION

3.1 Composite with Fiber orientation 45º-135º

This research offers a comprehensive and detailed investigation into critical parameters influencing composite materials' mechanical performance. This study sets itself apart by systematically exploring a wide range of fiber volume fractions (FVF) and fiber orientations, areas often not exhaustively studied in combination. Utilizing advanced ANSYS simulation techniques, it examines the impact of varying FVF, including less commonly explored ranges, to provide a deeper understanding of how fiber content affects bending strength. Additionally, the research investigates a broad spectrum of fiber orientations, including off-axis angles, to uncover nuanced effects on bending performance [9], [10]. This approach offers a thorough understanding of the anisotropic nature of composites and their behavior under different loading conditions. By leveraging refined meshing techniques and detailed finite element models, the ANSYS simulations provide precise predictions of failure mechanisms and mechanical properties, offering new insights and improvements over traditional empirical methods [11], [12]. The findings of this study have significant practical implications, guiding the design of more efficient and stronger composite materials by identifying optimal combinations of FVF and fiber orientation, ultimately contributing to innovations in composite manufacturing and application

The classification of results obtained from the bending tests conducted on composites with a fiber orientation of 45º-135º demonstrates a clear trend. The data from the graph highlights that the maximum tensile strength is achieved at higher ratios of fiber volume fractions. Notably, the highest recorded value from the bending test for the specific 45º -135º fiber orientation is 149.95 MPa.

Table 1. Bending Stress on Fiber Orientation 45º and 90º

Fiber Volume Fraction	Bending Stress (MPa) 45º	Bending Stress (MPa) 90º
0,25	73,968	85,11
0,30	85,927	99,209
0,35	99,025	114,35
0,40	113,57	130,85
0,45	130,08	149,25
0,50	149,95	170,41

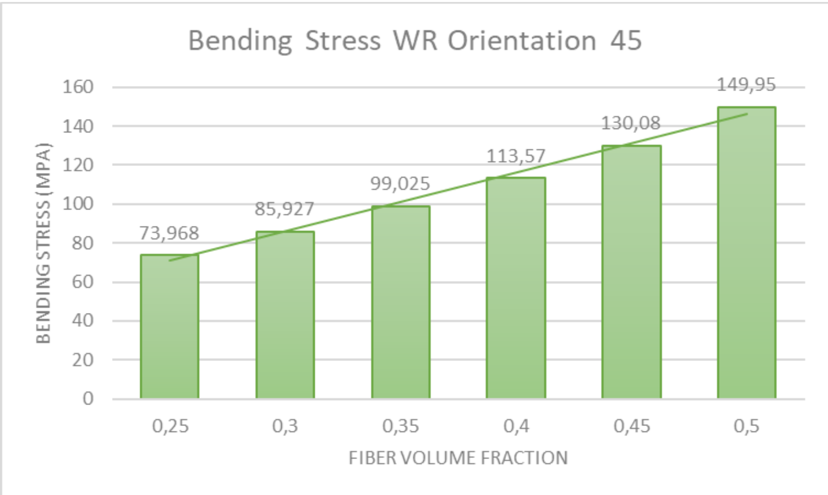

Figure 4. Graph Results of the Bending Test in the 45º-135º fiber orientation

In the results of the 3-point bending test, where the specimen had a configuration of a 50% fiber volume fraction and a 45º fiber orientation, a noteworthy outcome emerged. The test revealed a maximum stress of 149.95 MPa, signifying the point at which the material exhibited its highest resistance to deformation under the applied load. This impressive result was complemented by a corresponding strain value of 1.54%, indicating the extent of deformation or elongation experienced by the material during the bending test. These findings provide valuable insights into the mechanical behavior of the composite in this specific configuration and orientation, shedding light on its strength and flexibility under bending conditions shown in figure 5.

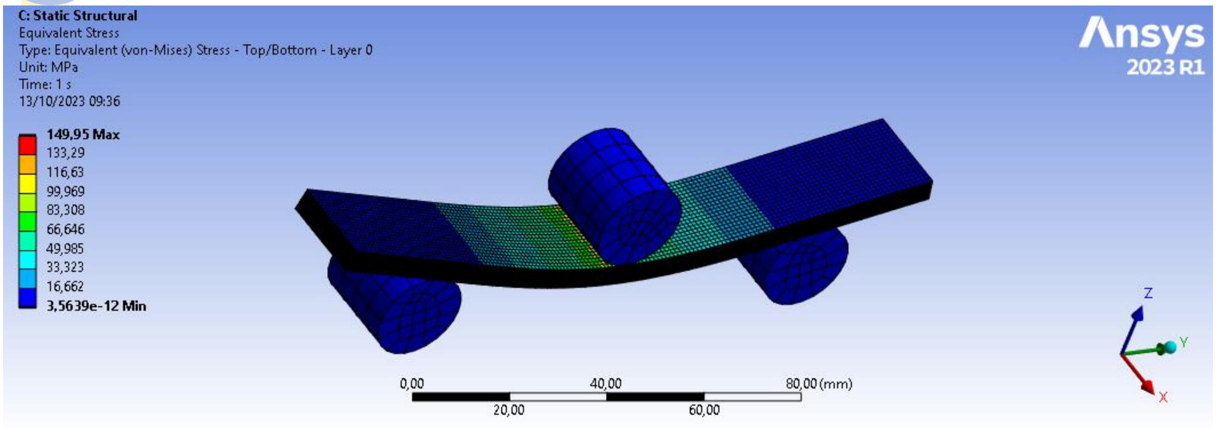

Figure 5. Simulation Results of the Bending Test (0.5-45°)

3.2 Composite with Fiber orientation 0°-90°

The findings represent the outcome of categorizing the results obtained from the bending tests conducted on composites with a fiber orientation of 0°-90°. An analysis of the accompanying graph reveals a clear trend: the highest tensile strength is achieved at higher ratios of fiber volume fractions. Specifically, the bending test for the 0o-90o fiber orientation yielded an impressive value of 170.41 MPa, indicating the material's remarkable resistance to deformation under the applied load. These results provide valuable insights into the mechanical characteristics of the composite in this particular orientation, underscoring its exceptional strength when subjected to bending forces.

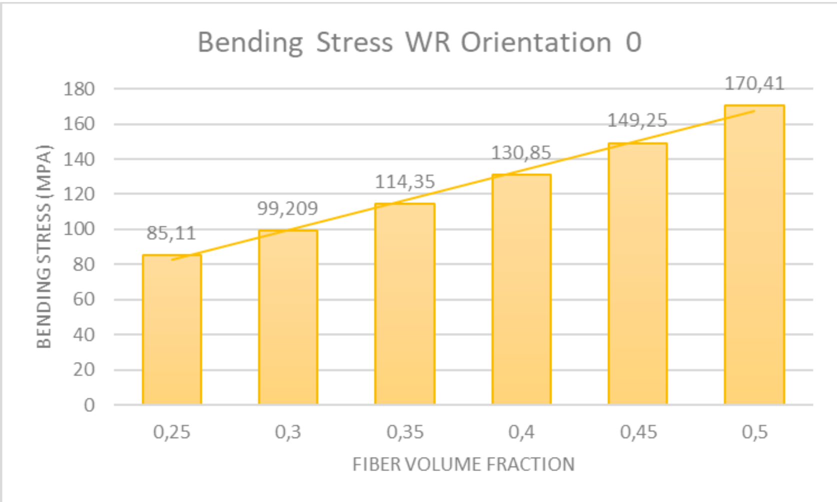

Figure 6. Graph Results of the Bending Test in the 0°-90° fiber orientation.

The 3-point bending test conducted on the specimen with a 50% fiber volume fraction and a 0° fiber orientation demonstrated a significant outcome. It exhibited a notable maximum stress of 170.41 MPa, reflecting the material's impressive ability to withstand bending forces. Additionally, the corresponding strain value of 1.5% indicated the extent of deformation experienced by the material during the bending test. These results provide valuable insights into the specimen's mechanical performance under specific bending conditions, highlighting its robustness and resilience as shown as Figure 7.

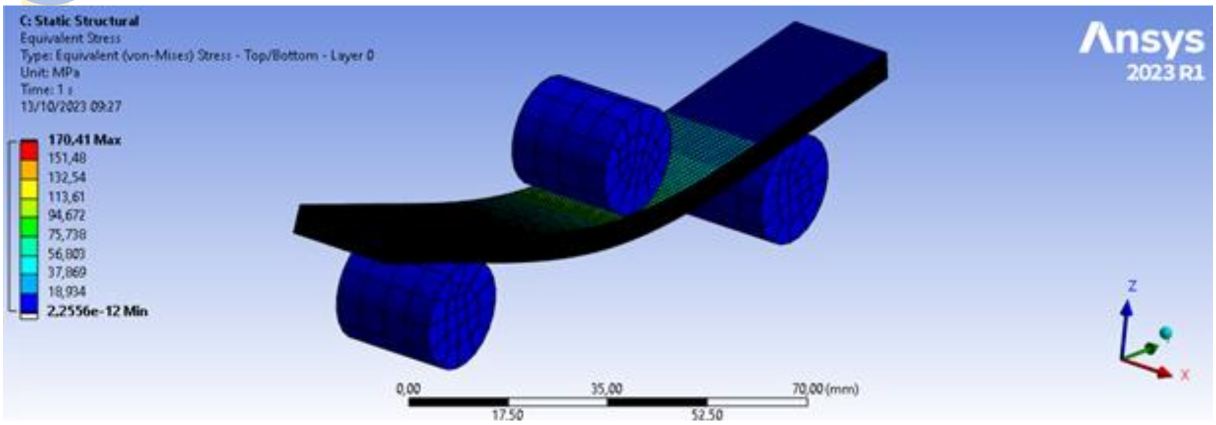

Figure 7. Simulation Results of the Bending Test in the 0º-90º fiber orientation

4. CONCLUSION

The rule of mixtures is a basic principle used to estimate the properties of a composite material based on the properties of its constituents. For composite materials, the rule of mixtures provides a way to predict the overall mechanical properties of the composite based on the properties of the individual components and their volume fractions. The rule assumes that the composite's properties are directly related to the volume fractions and properties of its constituents.

The flexural strength of the E-glass/polyester composite exhibits an upward trend with an increase in the ratio of the fiber volume fraction. Additionally, it is evident that the maximum value recorded during the bending test consistently aligns with the woven fiber orientation in the 0-90º direction. Notably, the pinnacle of the bending test, measuring 170.41 MPa, was achieved at the specific combination of a 0.5 Fiber Volume Fraction and the 0-90º fiber orientation. These observations highlight the significant influence of both fiber volume fraction and fiber orientation on the overall mechanical behavior of the composite, emphasizing their crucial roles in enhancing the composite's resistance to bending forces.

5. ACKNOWLEDGEMENT

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