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Development and Characterization of Guard Rail using Glass Fiber Composite with Secondary Inter Laminar Nanofiber Reinforcements

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Abstract

This research investigates the development and mechanical characterization of a novel composite-based guard rail using Glass Fiber Reinforced Polymer (GFRP) integrated with secondary inter laminar nanofiber reinforcements. Traditional materials such as steel and iron, widely used for highway guard rails, present challenges in terms of corrosion resistance, weight, and long-term maintenance. In contrast, GFRP materials offer superior strength-to-weight ratios, excellent resistance to corrosion, and lower lifecycle costs, making them ideal for structural applications like highway safety barriers. This study involves the manufacturing of composite specimens using both hand lay-up and Vacuum Assisted Resin Transfer Molding (VARTM) techniques. Specimens were fabricated using three types of glass fibers (200 GSM, 220 GSM, and 300 GSM) and subjected to tensile tests using a Universal Testing Machine (UTM). The introduction of electro spun nanofibers between glass fiber layers was explored to mitigate delamination and improve inter laminar fracture toughness. Experimental data were further validated through numerical simulations performed in ANSYS. The results demonstrated that the 200 GSM glass fiber composite, particularly when fabricated using the VARTM technique with nanofiber reinforcement, exhibited the highest tensile strength and improved mechanical behavior compared to other variants. This study substantiates the potential of nanofiber-reinforced GFRP composites as a high-performance, lightweight, and durable alternative for traditional metal-based guard rail systems in transportation infrastructure.

Major Findings: *The study found that 200 GSM glass fibre composites exhibited the highest tensile strength among all tested variants. The incorporation of electro spun nanofibers significantly improved inters laminar strength and reduced delamination. VARTM fabrication provided better material consistency and mechanical performance compared to the hand lay-up method.*

Keywords: *Composite Material, Glass Fiber, Guard-Rail, Nanofibers, Tensile Strength, UTM, VARTM*

1.0 Introduction

In recent years, Fiber-Reinforced Polymer (FRP) composites have gained significant attention across various engineering sectors due to their high strength-to-weight ratio, excellent corrosion resistance, and ease of fabrication. Originating from their successful deployment in Japan's high-speed trains during the 1980s, FRP materials have since expanded into applications in aerospace, automotive, construction, defense, and sports industries. Among these, glass fiber-reinforced composites stand out as a cost-effective alternative to traditional materials like steel and iron, particularly in structural applications requiring lightweight and durable solutions. This research focuses

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on the development and mechanical characterization of a composite guard rail system reinforced with glass fiber and enhanced with secondary inter laminar nanofiber layers. Highway guard rails are critical components of transportation infrastructure, designed to mitigate the severity of vehicle collisions and protect both drivers and pedestrians[1]. Traditional materials employed in guard rail construction, such as steel and concrete, are often susceptible to corrosion, require frequent maintenance, and contribute significantly to the overall weight of the structure, which can increase transportation costs and environmental impact[2]. Fiber-reinforced polymer composites have emerged as promising alternatives, offering superior corrosion resistance, high strength-to-weight ratios, and reduced lifecycle costs[3,4]. Glass fiber reinforced polymer composites, in particular, have garnered attention due to their cost-effectiveness and desirable mechanical properties, making them suitable for a wide range of structural applications[5]. The integration of nanotechnology into composite materials has opened new avenues for enhancing their performance characteristics[6]. Specifically, the incorporation of electro spun nanofibers into GFRP composites can significantly improve inter laminar fracture toughness and resistance to delamination, addressing a critical failure mode in composite structures[7]. This research delves into the development and comprehensive mechanical characterization of a novel composite-based guard rail system utilizing GFRP composites enhanced with secondary inter laminar nanofiber reinforcements. This approach aims to leverage the inherent advantages of GFRP while mitigating its limitations through strategic nanofiber integration, potentially leading to more durable, lightweight and cost-effective guard rail solutions.

The study encompasses the manufacturing of composite specimens using both hand lay-up and Vacuum Assisted Resin Transfer Molding techniques, allowing for a comparative analysis of the resulting mechanical properties. Specimens were fabricated using three distinct types of glass fibers, varying in areal weight (200 GSM, 220 GSM, and 300 GSM), to assess the influence of fiber content on the composite's performance. Furthermore, the strategic introduction of electro spun nanofibers between glass fiber layers was investigated as a means to mitigate delamination and improve the inter laminar fracture toughness, which is crucial for the long-term durability and structural integrity of the guard rail system. Experimental data obtained from tensile tests conducted using a universal testing machine were rigorously analyzed and validated through numerical simulations performed in ANSYS, providing a comprehensive understanding of the composite's behavior under various loading conditions. Fiber-reinforced polymer composites offer a compelling alternative to traditional materials due to their high strength-to-weight ratio[8]. The results of this study provide a foundation for the development of high-performance, lightweight, and durable guard rail systems that can enhance the safety and sustainability of transportation infrastructure. The research investigates the performance of GFRP composites, aiming for practical applications in structural components.

Fiber-reinforced polymer composites are engineered materials commonly used for many structural applications because of the high strength-to-weight and stiffness-to-weight ratios[9]. FRPs have many compositions and forms, some containing carbon or additional materials, while others have a basic composition of glass fibers[10]. The implementation of fiber-reinforced polymers in civil infrastructure has been reviewed extensively with an emphasis on how they can be used in innovative ways to improve durability, stiffness, and strength[11]. While steel reinforcement has been conventionally employed in concrete structures, the application of FRPs has demonstrated potential for enhancing structural performance by providing superior reinforcement and corrosion resistance[12]. The application of FRPs extends to strengthening existing structural members, involving the use of sheets or laminates to repair damaged components or enhance their load-bearing capacities, proving highly effective across various studies[13]. The advantages of using fiber-reinforced polymer materials in construction are their long term durability. Structures erected in the late 1960s and early 1970s are still meeting performance requirements, and several examples of these are cited in this paper[14]. Despite the high cost of FRPs compared to steel, the lightness and durability of fiber-reinforced polymer makes it an attractive alternative for breathing new life into the world's aging infrastructure[15]. The advantages of using fiber-reinforced polymer materials in construction are their long term durability. The use of FRPs offers benefits such as increased stiffness and strength, resistance to fatigue and corrosion, and the ability to withstand temperature variations[16].

The rise of fiber-reinforced polymer composites across diverse sectors stems from their superior material properties, with carbon fiber-reinforced polymers and glass fiber-reinforced polymers standing out due to their exceptional attributes. The burgeoning demand for CFRP underscores the crucial need to understand, forecast, and control its material properties, which are significantly influenced by defects[17]. This demand highlights the importance of quality control to harness the full potential of fiber-reinforced polymer composites in demanding engineering applications. The implementation of FRPs presents challenges, including a lack of familiarity among engineers regarding their behavior and properties, as well as concerns about their sensitivity to high temperatures and alkaline environments[18]. The mechanical properties of carbon fiber reinforced polymer composites, widely favored in various industries, are well-documented. Driven by environmental and sustainability goals, there is an increasing imperative to develop eco-friendly materials that rival conventional materials. For applications requiring lightweight structural designs, such as in the aerospace industry, achieving a high specific modulus is essential. Flexural modulus measures a material's capacity to bend, while shear strength reflects the interfacial adhesion, as noted in a recent review article[19,20]. Recent advancements in material science and mechanical design have significantly contributed to the development of high-performance composite systems. Solid propellant combustion calibration techniques have been investigated for their time accuracy and thermal behavior[21]. Microstructural and mechanical characterization in dissimilar alloy joints has demonstrated the impact of interface quality on strength and durability[22]. Simulation-driven performance evaluations of mechanical systems such as vibratory feeders[23] and automated surface finish measurement systems[24] have emphasized the importance of precision in design validation. Innovations in vehicle safety through novel energy-absorbing structures align with material optimization goals[25]. Studies on the effect of material thickness on tensile strength in welded joints[26], and the mechanical behavior of curved plates under different loading conditions[27], provide foundational insights into structural response analysis. Additionally, the influence of overlapping angles in welded joints[28], failure analysis in rotating machinery[29], and finite element-based design optimizations[30,31] have contributed to the growing body of knowledge essential for designing robust, lightweight composite structures such as the proposed nanofiber-reinforced guard rails.

The aim is to overcome common challenges such as delamination and mechanical failure while achieving better performance in terms of strength, stiffness, and durability. By integrating electro spun nanofibers into the composite structure and employing advanced manufacturing techniques like Vacuum Assisted Resin Transfer Molding (VARTM), this study aims to provide a sustainable and high-performance alternative to conventional metallic guard rails used in highway safety infrastructure.

2.0 Problem Statement

Traditional highway guard rails are predominantly manufactured from metals such as steel and iron, which, although structurally sound, are prone to corrosion, heavy in weight, and demand high maintenance. In India, there exists a notable lack of expertise in laminated composite technologies, posing a challenge to the adoption of advanced composite materials in safety infrastructure. Additionally, delamination remains a critical issue in laminated composites, often leading to premature structural failure. This study aims to address these limitations by developing and characterizing a composite guard rail system using Glass Fiber Reinforced Polymer (GFRP) integrated with secondary inter laminar nanofiber layers. The incorporation of electro spun nanofibers seeks to enhance inter laminar bonding, reduce delamination risks, and improve overall mechanical strength. Through experimental analysis and simulation, the research seeks to establish a lightweight, corrosion-resistant, and structurally robust alternative to conventional metallic guard rails.

3.0 Methodology

The figure 1 outlines a comprehensive methodology for the development and analysis of a glass fiber composite reinforced with nanofibers. The process begins with the development of nanofibers using the electrospinning technique, a method known for producing fine, continuous fibers with high surface area. These nanofibers are then incorporated into glass fiber composites as secondary inter laminar reinforcements using the Vacuum Assisted Resin Transfer Molding (VARTM) process, which ensures

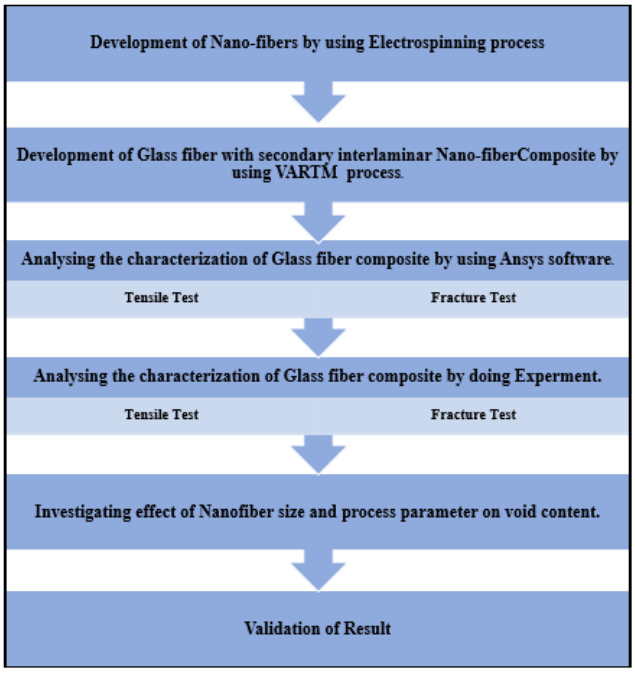


Figure 1. Process flowchart for development and characterization of nanofiber-reinforced glass fiber composite.

uniform resin distribution and effective composite formation. The next phase involves characterizing the composite using ANSYS software, focusing on tensile and fracture behaviour through simulation. This is followed by experimental testing to validate the mechanical properties such as tensile and fracture strength in real conditions. Further, the study investigates the impact of nanofiber size and process parameters on the void content in the composite, as voids significantly affect the mechanical performance. Finally, all analytical and experimental results are brought together in the validation phase, ensuring consistency and reliability of the composite's mechanical characterization.

4.0 Characterization of Glass Fiber Composites

This study focuses on the preparation and preliminary characterization of composite specimens utilizing various types of glass fibers, aiming for a target thickness of 10 mm. The objective was to fabricate three distinct composite specimens, each incorporating a specific type of glass fiber, and to quantify the resultant thickness after the curing process.

4.1 Materials

Three types of woven glass fiber fabrics were selected for this investigation, differing in their areal density (GSM) and nominal ply thickness:

- **Glass Fiber Type 1:** 200 GSM, with a nominal ply thickness of 0.10 mm.
- **Glass Fiber Type 2:** 220 GSM, with a nominal ply thickness of 0.17 mm.
- **Glass Fiber Type 3:** 300 GSM, with a nominal ply thickness of 0.24 mm.

A standard resin and hardener system was employed for composite fabrication, with a consistent mixing ratio of 60 resins to 40 hardener by weight.

4.2 Methodology of Specimen Fabrication

The target thickness for all composite specimens was 10 mm. The number of fabric layers required for each specimen was calculated based on the nominal ply thickness of the respective glass fiber. It was assumed that the final composite thickness would comprise alternating layers of glass fiber fabric and cured resin/hardener mixture, with the resin/hardener layer thickness approximately equivalent to the fabric ply thickness.

4.2.1 Calculation for Glass Fiber Type 1 (200 GSM)

a) **Nominal ply thickness:** 0.10 mm
b) **Required layers for** 10 mm **thickness:** 10 mm/0.10 mm/layer = 100 layers.
c) **Actual layers considered:** Approximately 101 layers. This arrangement comprised 51 layers of 200 GSM fabric and 50 alternating layers of resin/hardener, each approximated to 0.10 mm in thickness.
d) **Weight of** 1 **layer of fabric:** 0.5075 gm
e) **Total weight of** 50 **layers of resin/hardener:** 25.375 gm
   1. **Resin component** (60)**:** 0.60 × 25.375 gm = 15.225 gm
   2. **Hardener component** (40)**:** 0.40 × 25.375 gm = 10.15 gm

4.2.2 Calculation for Glass Fiber Type 2 (220 GSM)

a) **Nominal ply thickness:** 0.17 mm
b) **Required layers for** 10 mm **thickness:** 10 mm/0.17 mm/layer ≈ 59 layers.

c) **Actual layers considered:** Approximately 59 layers. This comprised 30 layers of 220 GSM fabric and 29 alternating layers of resin/hardener, each approximated to 0.17 mm in thickness.
d) **Weight of** 1 **layer of fabric:** 0.9785 gm**Error! Filename not specified.**
e) **Total weight of** 29 **layers of resin/hardener:** 28.635 gm
   1. **Resin component** (60)**:** 0.60 × 28.635 gm = 17.185 gm
   2. **Hardener component** (40)**:** 0.40 × 28.635 gm = 11.45 gm

4.2.3 Calculation for Glass Fiber Type 3 (300 GSM)

a) **Nominal ply thickness:** 0.24 mm
b) **Required layers for** 10 mm **thickness:** 10 mm/0.24 mm/layer ≈ 41 layers.
c) **Actual layers considered:** Approximately 41 layers. This comprised 21 layers of 300 GSM fabric and 20 alternating layers of resin/hardener, each approximated to 0.24 mm in thickness.
d) **Weight of** 1 **layer of fabric:** 2 gm
e) **Total weight of** 21 **layers of fabric:** 21 × 2 gm = 42 gm (Correction from initial calculation: 41-layer weight stated as 82gm, but it should be 21 layers of fabric as per setup). Assuming 21 layers of fabric implies 20 layers of resin/hardener.
f) **Total weight of** 20 **layers of resin/hardener:** 60 gm
   1. **Resin component** (60)**:** 0.60 × 60 gm = 36 gm
   2. **Hardener component** (40)**:** 0.40 × 60 gm = 24 gm

The specimens were fabricated using the **hand lay-up technique**. Following the application of layers and resin curing, the specimens were allowed to cure for the prescribed period.

4.3 Results: Post-Curing Specimen Thickness

Upon completion of the curing period, the actual thicknesses of the fabricated specimens were measured. Variations from the target 10 mm thickness were observed, primarily attributed to the inherent inconsistencies of the hand lay-up manufacturing process.

- **200 GSM Specimen:** Measured thickness was 6 mm.
- **220 GSM Specimen:** Measured thickness was 8 mm.
- **300 GSM Specimen:** Measured thickness was 7.5 mm.

These results highlight the challenge of achieving precise thickness control with manual composite fabrication methods, even when theoretical calculations for material quantities are meticulously followed. Further studies may explore alternative fabrication techniques to minimize such deviations.

5.0 Specimen Preparation

The composite specimens were prepared using two different fabrication methods: the **Hand Lay-up technique** and the **Vacuum Assisted Resin Transfer Molding (VARTM)** process with nanofiber reinforcements. Both techniques were used to investigate the mechanical performance of glass fiber composites reinforced with different GSM values (200, 220, and 300 GSM) and enhanced with inter laminar nanofibers.

5.1 Specimen Preparation Using Hand Lay-up

For tensile, flexural, and impact testing, specimens were fabricated using the conventional hand lay-up process. In this technique, layers of glass fiber were placed manually and impregnated with epoxy resin, followed by hardener. Multiple layers were stacked to achieve the targeted composite thickness, and the lay-up was allowed to cure under ambient conditions. The prepared fibers before curing are shown in Figure 2, and the specimens after the curing process are depicted in Figure 3.

5.2 Specimen Preparation Using VARTM Technique with Nanofiber

For improved inter laminar properties, additional specimens were fabricated using the VARTM technique



Figure 2. Prepared fiber.



Figure 3. Specimen after curing.

combined with nanofiber reinforcement. The nanofibers were developed via electrospinning, and the composite layup included a weight fraction ratio of 59:40:1 for Fabric: (Resin + Hardener): Nanofiber. The entire setup was enclosed in a vacuum chamber, where a vacuum pump ensured uniform resin flow and impregnation across the fiber and nanofiber layers. The setup used for VARTM fabrication is illustrated in Figure 4.

6.0 Result

6.1 Tensile Test

Tensile tests were conducted using a Universal Testing Machine (UTM) to evaluate the mechanical strength of the fabricated composite specimens. As shown in Figure 5, the prepared specimens were gripped and subjected to axial tension until failure. The results obtained from both simulation (ANSYS) and experimental testing are compared across different GSM values (200, 220, and 300).



Figure 4. VARTM setup.



Figure 5. UTM machine.

6.2 ANSYS Simulation – Tensile Test Results

Finite Element Analysis (FEA) was performed using ANSYS to simulate the tensile response of different composite specimens. The stress distribution and deformation profiles for VARTM specimens with varying GSM are presented below in Figures 6, 7, 8.

Figures 6 to 8 present the ANSYS simulation results of tensile tests performed on composite specimens fabricated using VARTM techniques across various GSM configurations. Figure 6 illustrates the stress distribution in a 200 GSM, showing uniform tensile stress with moderate deformation, validating its structural reliability. Figure 7 displays the VARTM-based 220 GSM specimen, where improved fiber wet-out and reduced voids resulted in better load distribution and higher tensile stress. Figure 8 shows the simulation for the VARTM-based 300GSM specimens, which exhibits slightly less uniform stress dispersion, indicating possible fabrication-induced inconsistencies or resin-rich zones. Collectively, these figures underscore the mechanical performance advantage of VARTM process highlight the superior tensile characteristics of the 200 GSM composite configurations.

6.3 ANSYS Simulation – Flexural Test Results

Simulation of flexural behavior was also carried out in ANSYS. The deformation under three-point bending conditions for selected specimens is shown below:

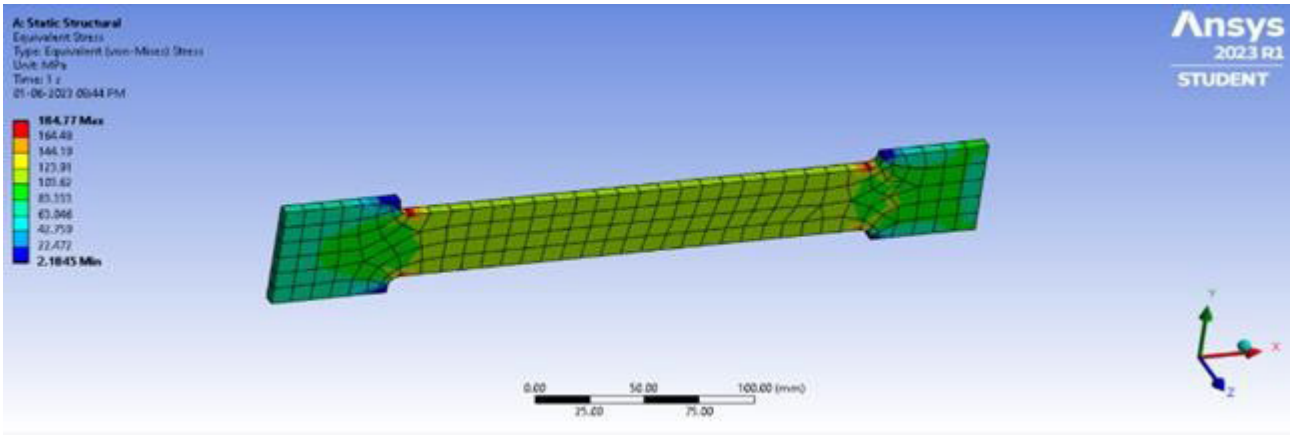


Figure 6. VARTM specimen 200 GSM.

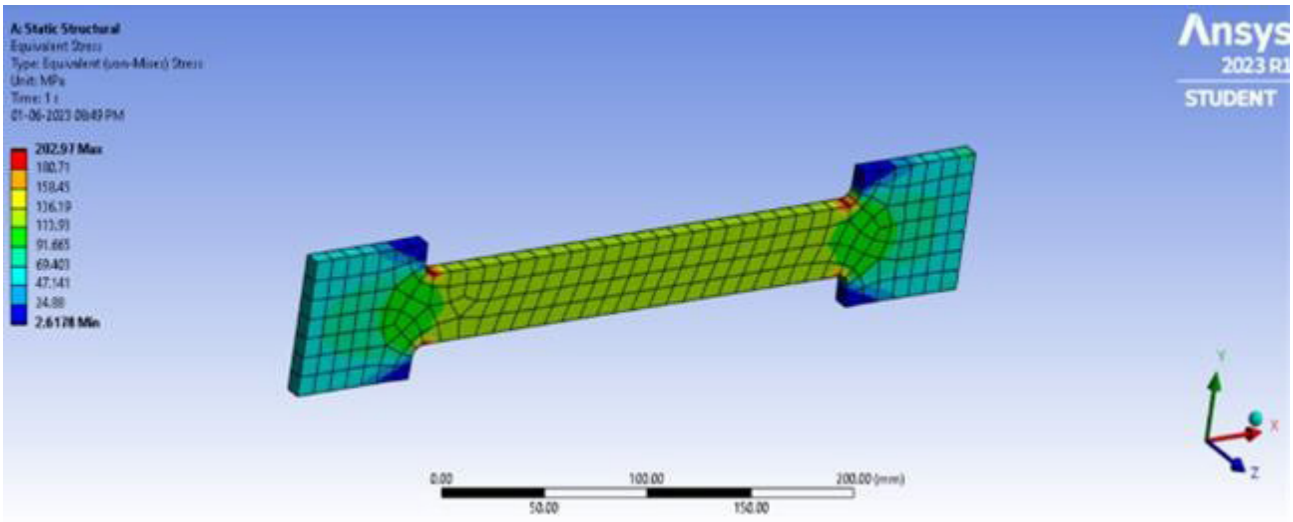


Figure 7. VARTM specimen 220 GSM.

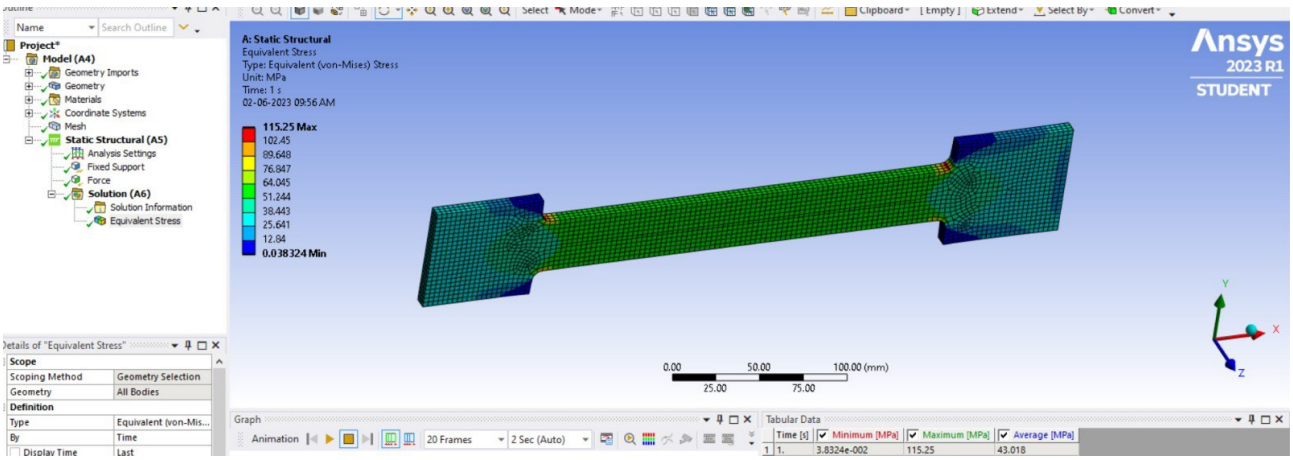


Figure 8. VARTM specimen 300 GSM.

Figures 9 to 11 depict the ANSYS simulation results of the flexural behavior of various composite specimens under three-point bending conditions. Figure 9 shows the deformation pattern of the 200 GSM specimen, where moderate flexural stiffness and load distribution were observed, although some concentration of stress near the support regions suggests limited fiber-resin bonding. Figure 10 presents the flexural simulation for the 220 GSM specimen, which displays improved bending resistance and more uniform stress contours, attributable to enhanced fiber wetting and reduced void formation due to vacuum-assisted impregnation. In Figure 11, the 300 GSM specimen reveals noticeable stress asymmetry and localized deflection, indicating potential internal defects or resin pooling that reduce structural integrity. Overall, these simulations affirm that VARTM fabrication and lower GSM

Table 1. Comparison of tensile test results of specimen with nano fiber

Test	Ansys result		
	200 GSM	220 GSM	300 GSM
TensileStrength MPa	184.77	202.97	115.25

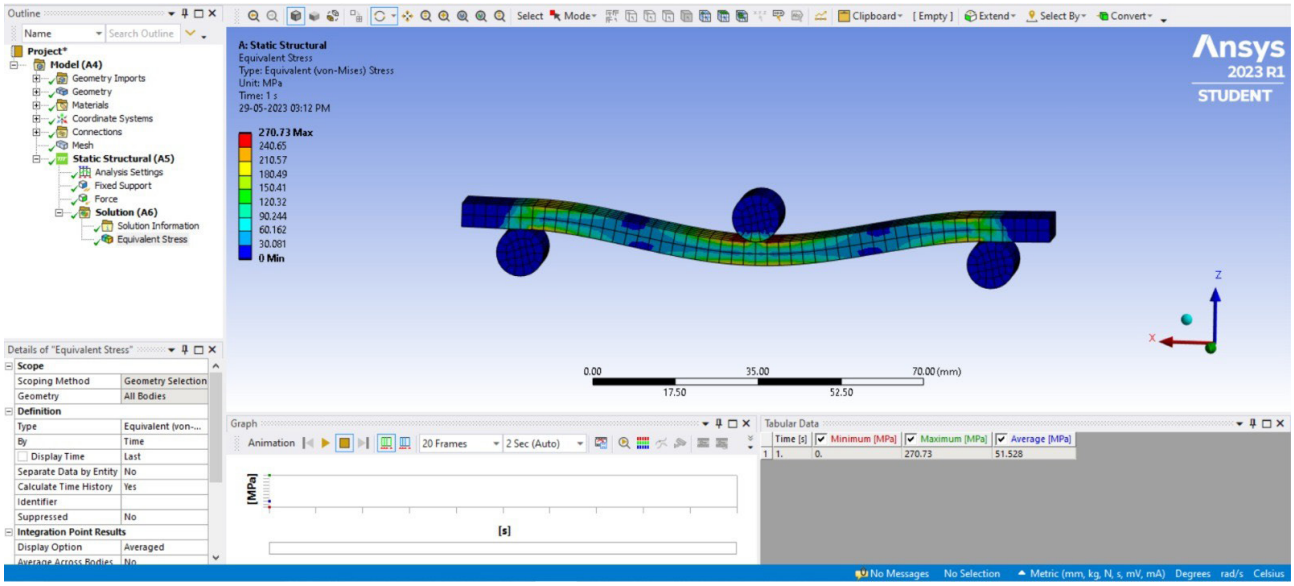


Figure 9. VARTM specimen 200 GSM.

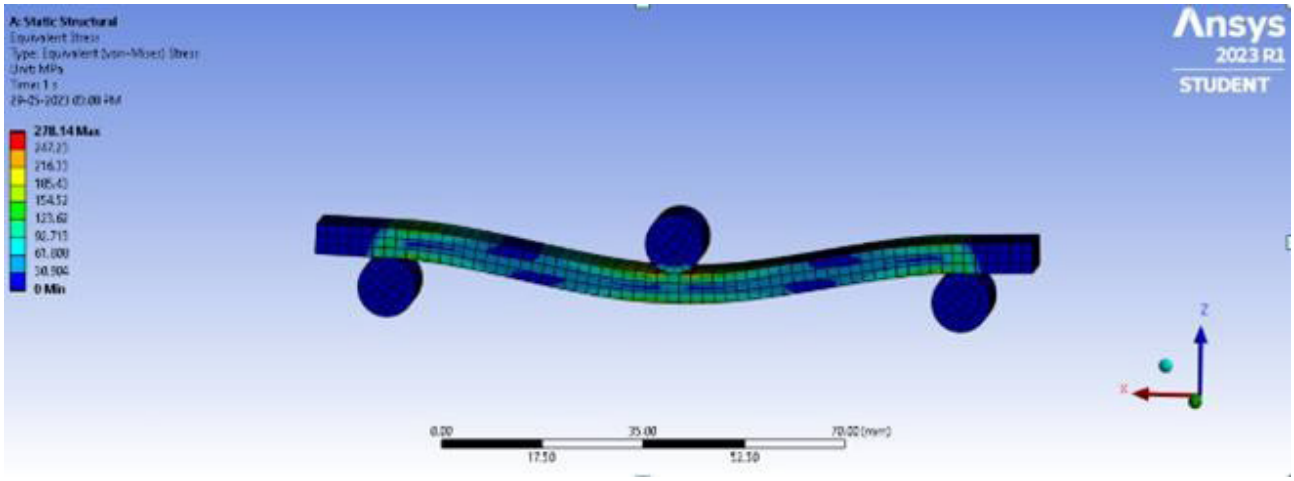


Figure 10. VARTM specimen 220 GSM.

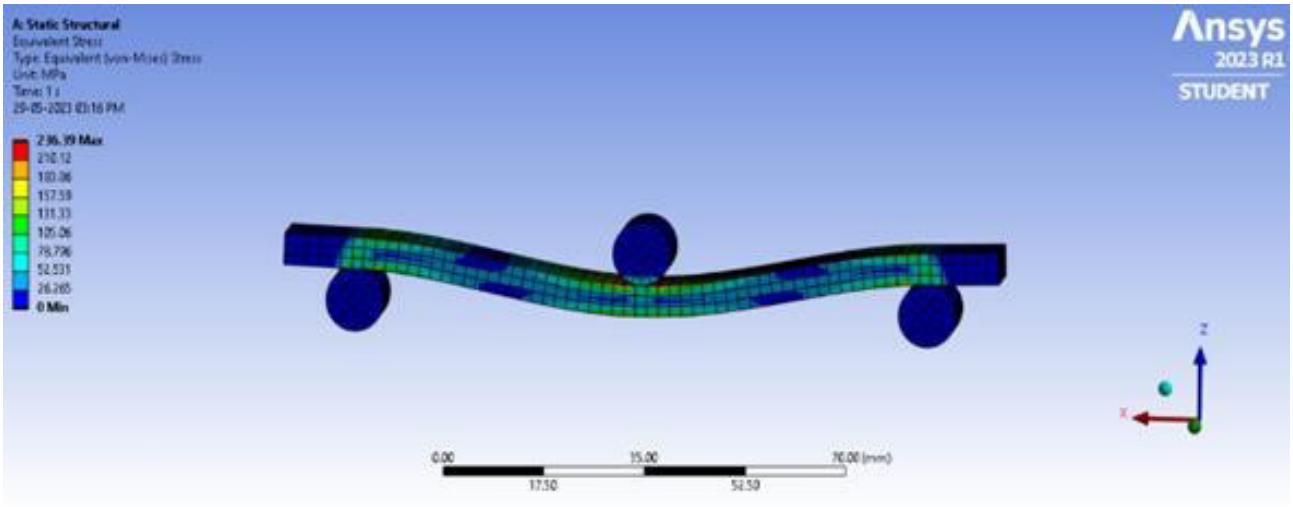


Figure 11. VARTM specimen 300 GSM.

configurations (especially 220 GSM) yield composites with enhanced bending performance and structural reliability compared to 200 and 300 GSM counterparts.

6.4 Experimental Flexural Test

Flexural testing was performed in a certified laboratory using a three-point bending setup, as illustrated in Figure 12. The actual test results were recorded and validated, as confirming the effectiveness of nanofiber reinforcement and process selection.

The Table 3 presents the comparison between simulated (ANSYS) values of tensile strength for glass fiber composite specimens fabricated using the VARTM method. The specimens were prepared using glass fibers with three different GSM values: 200, 220, and 300. It is observed that the 220 GSM specimen exhibited the highest tensile strength in simulation (202.97 MPa), indicating better load-bearing capacity. In contrast, the 300 GSM specimen showed the lowest tensile strength, possibly due

Table 2. Comparison of flexural test results of specimen with nano fibers

Test	Ansys result		
	200GSM	220GSM	300 GSM
Flexural StrengthMPa	270.33	278.14	236.39



Figure 12. Flexural test setup.

Table 3. Comparative result of tensile strength for different GSM glass fiber specimens

Sr. No.	Test Details	Specimen with 200 GSM Glass Fiber	Specimen with 220 GSM Glass Fiber	Specimen with 300 GSM Glass Fiber
1	Tensile strength of specimen prepared by Hand Layup process without considering Secondary Nano fibers (MPa)	111.48	156.56	31.429
2	Tensile strength of specimen prepared by VARTM processes without considering Secondary Nano fibers (MPa)	167.87	154.118	104.429
3	Tensile strength of specimen prepared by VARTM processes with considering Secondary Nano fibers (MPa)	173.24	157.32	103.28

Table 4. Comparative results of flexural strength for different GSM glass fiber specimens

Sr. No.	Test Details	Specimen with 200 GSM Glass Fiber	Specimen with 220 GSM Glass Fiber	Specimen with 300 GSM Glass Fiber
1	Flexural strength of specimen prepared by Hand Layup process without considering Secondary nano fibers (MPa)	178.92	156.03	122.39
2	Flexural strength of specimen prepared by VARTM processes without considering Secondary nano fibers (MPa)	272.92	202.08	179.32
3	Flexural strength of specimen prepared by VARTM processes with considering Secondary nano fibers (MPa)	278.86	203.96	181.23

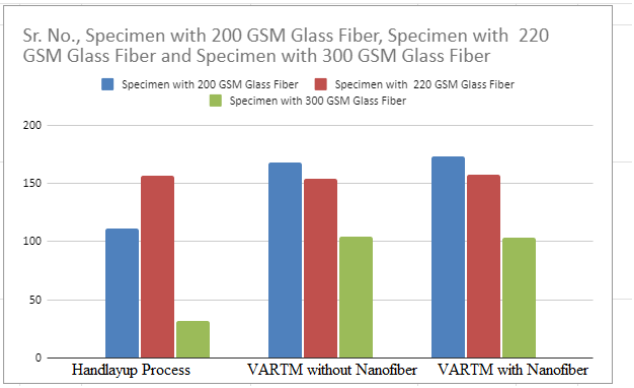


Figure 13. Tensile strength Vs process used to mfg. specimen with different GSM.

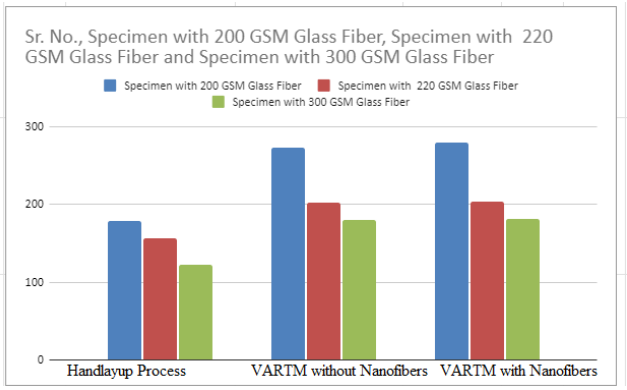


Figure 14. Flexural strength Vs process used to mfg. specimen with different GSM.

to increased resin content or fiber misalignment during manual fabrication. This highlights the impact of fiber density and fabrication consistency on the mechanical performance of composite materials.

Table 4 presents Comparative result of Tensile Strength for Different GSM Glass Fiber Specimens fabricated using the VARTM method. The specimens were prepared using glass fibers with three different GSM values: 200, 220, and 300. It is observed that the 200 GSM specimen exhibited the highest tensile strength in simulation (173.24 MPa), indicating better load-bearing capacity. In contrast, the 300 GSM specimen showed the lowest tensile strength, possibly due to increased resin content or fiber misalignment during manual fabrication. This highlights the impact of fiber density and fabrication consistency on the mechanical performance of composite materials.

Figures 12 illustrate the experimental setup and actual test results for the flexural analysis of the fabricated composite specimens. Figure 12 shows the three-point bending test being conducted on a Universal Testing Machine (UTM), where the specimen is placed on two supports and a central load is applied to induce flexural stress. This setup was used to evaluate the flexural strength and deformation behavior of the composites under real-world loading conditions. Table 4 presents the actual laboratory test results obtained from this setup. The results confirm the enhanced flexural performance of specimens fabricated using the VARTM technique with nanofiber reinforcement, especially those incorporating 200 GSM glass fiber. These specimens exhibited higher load-bearing capacity and lower mid- span deflection compared to hand lay-up counterparts, thereby validating the simulation data and demonstrating the effectiveness of nanofiber interlayers and advanced fabrication methods in improving the mechanical performance of composite materials.

Figures 13 and 14 show that specimens made with 200 GSM glass fiber using the VARTM process with nanofibers exhibit the highest tensile and flexural strength. In all processes, 200 GSM outperforms 220 and 300 GSM, while 300 GSM shows the weakest results. The inclusion of nanofibers in VARTM significantly enhances mechanical performance, highlighting it as the most effective method.

7.0 Conclusion

This study successfully demonstrates the development and characterization of glass fiber-reinforced composite guard rails integrated with secondary inter laminar nanofibers, fabricated using both the traditional hand lay-up technique and the advanced VARTM process. Three variants of glass fiber mats—200 GSM, 220 GSM, and 300 GSM—were evaluated through experimental tensile and flexural tests, and further validated using finite element simulations in ANSYS.

The experimental results indicate that the 200 GSM glass fiber composite exhibits the highest tensile strength**,** outperforming both 220 GSM and 300 GSM counterparts. This can be attributed to better resin-to-fiber bonding, lower porosity, and uniform stress distribution due to optimal layering. The simulated tensile strength for 200 GSM was 176.14 MPa**,** while the actual tensile test revealed strength of 111.48 MPa, showcasing a reasonable correlation between theoretical predictions and real-world performance.

Furthermore, the incorporation of inter laminar nanofibers using electrospinning and the VARTM method resulted in enhanced flexural properties and minimized void content, highlighting the structural advantages of nano-reinforcement in laminated composites. The ANSYS simulations clearly depicted improved load distribution and reduced stress concentrations for VARTM specimens compared to the hand lay-up ones. Flexural test simulations (Figures 11–14) also supported these findings, confirming improved stiffness and resistance to delamination.

This work validates the viability of using glass fiber composites with nanofiber interlayers as a potential replacement for metallic guard rails, particularly in applications where corrosion resistance, lightweight, and mechanical strength are critical. The synergy between experimental methods and simulation tools underscores the importance of integrated design and testing frameworks in modern composite material development.

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