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Comparative Study of Manufacturing Methods and Their Effect on Tensile and Flexural Properties of Glass/Epoxy Laminates

Siraj Kedir Busse *,1 **and Esmael Adem Esleman** *,2

*Department of Mechanical Engineering, School of Mechanical, Chemical and Materials Engineering, Adama Science and Technology University, Adama, Ethiopia.

ABSTRACT The utilization of composite materials has significantly surged in the aeronautics, automotive, military, and civil construction sectors, replacing conventional materials like steel, aluminum, and other alloys. Laminated composite materials possess elevated modulus-to-weight and strength-to-weight ratios, along with superior fatigue resistance and non-corrosive characteristics. This study aims to examine the influence of manual lay-up, vacuum bagging, and vacuum assisted resin transfer molding methods on the tensile and flexural properties of glass/Epoxy composites. The tensile and flexural test specimen was fabricated and evaluated in accordance with ASTM D3039 and ASTM D7264 standards, respectively. The samples were evaluated using a computer-controlled electro-hydraulic universal testing machine. The specimen was analyzed using a Scanning Electron Microscope (SEM) to assess the laminate's uniformity. The maximum tensile and flexural strength recorded for hand layup approach is 280 MPa and 320 MPa, respectively. Nevertheless, the vacuum bagging method yielded a better result than hand lay-up techniques. The results achieved during those tests were 330 MPa and 435 MPa, respectively. In contrast, the VARTM provides a superior tensile and flexural properties, i.e. 444.49 MPa and 560 MPa, respectively. The samples produced using the VARTM technique exhibit superior mechanical properties, demonstrating differences of 17.86%, 32.14%, and 35.94% in tensile, shear, and bending tests, respectively, compared to those made using hand layup. Consequently, the mechanical properties of the laminate were enhanced by vacuum bagging procedures compared to hand lay-up approaches.

KEYWORDS
Glass fiber composites
Hand lay-up
Vacuum bagging
VARTM
ASTM
SEM
Tensile strength
Flexural strength

INTRODUCTION

Fiber-reinforced polymer composites have gained significance in engineering applications due to their lightweight characteristics and superior mechanical qualities. Glass fiber reinforced epoxy composites are extensively utilized due to their affordability, favorable strength-to-weight ratio, and resistance to corrosion (Belingardi and Koricho 2014). The effectiveness of laminated composites is significantly influenced by constituent materials, fiber orientation, stacking sequence, and production methods.

The fabrication process greatly affects the mechanical performance of glass fiber reinforced epoxy (glass/epoxy) composites. The influencing parameters during fabrication are resin distribution, fiber wetting, void content and interfacial bonding. Therefore, the tensile and flexural properties will vary on the manufacturing technique (Belingardi and Koricho 2014; Esleman *et al.* 2015; Rajak *et al.* 2019).

Various fabrication methods are commonly utilized for GFRP laminates, such as hand lay-up, vacuum bagging, resin infusion, compression molding, and autoclave processing. Hand lay-up technique is one of the oldest and most common methods for composite manufacturing because of its simplicity and low production cost. However, different studies have reported higher void content,

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[1]siraj.kedir@astu.edu.et (**Corresponding author**).

resin-rich regions and non-uniform fiber impregnation in hand lay-up laminates, which negatively affect the mechanical properties of composites. Esleman EA et al. investigated E-glass/epoxy composites manufactured using traditional hand lay-up methods and found that matrix cracking, fiber pull-out, and delamination were defects that reduced tensile and flexural strength. Poor laminate consolidation also resulted in premature failure when subjected to loading; this was observed in the study (Esleman *et al.* 2015).

Raajeshkrishna and Chandramohan have examined the influence of fiber kinds and production techniques on the mechanical properties of glass/epoxy and basalt/epoxy composites (Raajeshkrishna and Chandramohan 2020). Their study employed vacuum bagging, vacuum-assisted resin infusion, and hand layup with compression manufacturing techniques to generate samples. The results indicate that samples fabricated using hand layup combined with compression molding exhibit superior mechanical qualities compared to the other two samples. Furthermore, Abdurohman et al. have investigated the influence of production processes on the mechanical properties of glass EW 185/lycal composites (Abdurohman *et al.* 2018). Hand lay-up, vacuum bagging, and vacuum infusion techniques were utilized to fabricate their samples. The results indicate that the vacuum infusion method was the superior production technique for enhancing the mechanical properties of the tested composites compared to other methods.

Additionally, Hennigan et al. have investigated the impact of hand layup, vacuum infusion, and their combination on the tensile and compressive parameters of GFRP composites (Hennigan and Beavers 2010). The results indicate that GFRP composite samples manufactured using the vacuum infusion approach exhibit enhanced tensile and compressive characteristics. Similarly, kenaf/polyester samples fabricated using the vacuum infusion process have superior tensile characteristics compared to those created via hand layup (Yuhazri and Sihombing 2010).

Cerbu et al. examined the influence of hand layup molding pressure on the mechanical characteristics of glass epoxy composites (Cerbu *et al.* 2008). The results reveal that the application of lower pressure has been diminishing the flexural strength of the composites. In another study, the tensile characteristics of GFRP composites were enhanced with increased hand layup molding pressure (Faizal *et al.* 2006).

Sawi et al. investigated the impact of production techniques (compression molding and autoclave) on the mechanical properties of flax/epoxy composites (Sawi *et al.* 2014). Authors advocated using compression molding over autoclaving to enhance the mechanical properties of flax/epoxy samples.

In composite manufacturing, the vacuum-assisted techniques like vacuum bagging and Vacuum Assisted Resin Transfer Molding (VARTM) have been increasingly used to enhance the quality of laminates. Vacuum bagging is the practice of applying external pressure during cure to improve compaction of the laminate, and to remove trapped air and excess resin. Boransan et al. compared the hand lay-up and vacuum bagging techniques for glass fiber composites and found that vacuum bagging significantly enhanced the flexural strength and minimized the structural defects due to increased fiber wetting and decreased porosity (Boransan *et al.* 2021).

VARTM is one of the most efficient low cost manufacturing methods for production of quality composite laminates. The resin flow under vacuum pressure impregnates dry fiber layers during this process which leads to better resin penetration and uniform laminate structure. Talabari et al. experimentally compared glass/epoxy composites for hand lay-up, vacuum bagging and vacuum infusion fabrication methods (Talabari *et al.* 2019). The author reported that vacuum infusion achieved roughly 20% more tensile strength than manual lay-up, attributed to decreased voids and enhanced interlaminar bonding.

Rydarowski and Koziol et al. performed a similar study on the repeatability and mechanical behavior of glass fiber reinforced polymer laminates produced by hand lay-up and vacuum-assisted resin infusion (Rydarowski and Koziol 2015). The study showed that vacuum assisted techniques lead to more uniform laminate thickness and lower variability of tensile properties than hand lay-up composites. Assunção, G. S. C. et. al. reported that the Resin Spraying with Vacuum Assisted Molding (RSVAM) technique produced an average tensile strength of 31 $\pm$ 3 MPa and a flexural strength of 157 $\pm$ 7 MPa, while the conventional spray-up process showed tensile and flexural strengths of approximately 30 $\pm$ 9 MPa and 155 $\pm$ 22 MPa, respectively. In addition, the RSVAM process significantly improved the Izod impact resistance to 107 $\pm$ 6 J/cm, which was about 168% higher than the conventional spray-up method (39.9 $\pm$ 2.8 J/cm) due to better laminate consolidation and reduced void content (Assunção *et al.* 2024).

Kubit A et al., showed that manufacturing method significantly affects the mechanical, fatigue, and morphological properties of CFRP composites, with autoclave processing providing the highest tensile strength ($\sim$619 MPa), flexural strength ($\sim$1088 MPa), and fatigue life ($\sim 678 \times 10^3$ cycles) due to superior compaction and minimal void content. In contrast, resin infusion and vacuum-assisted hand lay-up methods exhibited lower performance because of higher porosity and weaker fiber–matrix bonding, leading to reduced strength and fatigue resistance (Kubit *et al.* 2024).

Dewangan B, and Chakladar ND investigated that autoclave manufacturing produces higher tensile and flexural properties in glass/epoxy composites due to better consolidation and lower void content. Out-of-autoclave processes result in reduced mechanical performance because of higher porosity and weaker fiber–matrix bonding (Dewangan and Chakladar 2024).

Many studies have studied mechanical behavior of glass/epoxy composites but very few studies have compared the effect of hand lay-up, vacuum bagging and VARTM manufacturing techniques on tensile and flexural properties under similar fabrication conditions. Thus, the aim of this work is to experimentally compare these manufacturing techniques and assess their influence on the mechanical performance of glass/epoxy laminates.

MATERIALS AND METHODS

Materials

Woven glass fiber, detailed in Table 1, serves as reinforcement, while the epoxy resin is identified by the brands SYSTEM #2000 EPOXY RESINS and SYSTEM #2060 HARDNER. The supplier's manual specifies the ratio of net epoxy resin to hardener as 3:1 by volume or 100:27 by weight.

Methods

Manufacturing of Samples The Glass/Epoxy laminate specimens were fabricated using three different fabrication techniques, namely: Hand Lay-up, Vacuum Bagging and VARTM processes, as seen in Figure 1 (a–c). Upon combining the epoxy resin with the hardener, the mixture is applied to the fiber layers, and a brush is used to eliminate air bubbles during the hand layup procedure, as shown in Figure 1(b). The laminate was cured at room temperature for 24 hours in case of hand lay-up process. In the vacuum bagging procedure shown in Figure 1(a), a plastic sheet is employed

Table 1 Typical properties of E-Glass fiber used in this study

S/No.	Property	Unit	Value
1	Normal Thickness	mm	0.55
2	Weave type	Degree	Plain Woven (0, 90)
3	Density	gm/cc	2.6
4	Tensile Strength	MPa	2,500
5	Tensile Modulus	MPa	74,000
6	Elongation	Percent (%)	3.5

to seal the hand-laid laminate. Furthermore, a vacuum pump is utilized to eliminate air bubbles beneath the bag, so enabling the application of up to one atmosphere of pressure to consolidate and cure the laminate (Esleman *et al.* 2015; Rajak *et al.* 2019). Whereas, in VARTM as shown in Figure 1(c), dry glass fiber fabrics were placed on the mold and sealed using a vacuum bag. Resin was infused through the laminate under vacuum pressure. The process provided uniform resin flow and minimized void formation.



a) b) c)

Figure 1 Fabrication of composite specimen: (a) vacuum bagging, (b) hand lay-up method, and (c) VARTM method.

The composite specimens for tensile (220 mm × 20 mm × 2.5 mm) and flexural (150 mm × 20 mm × 4 mm) tests were prepared according to the ASTM standards (ASTM International 2008, 2007) and the picture depicted in Figure 2.

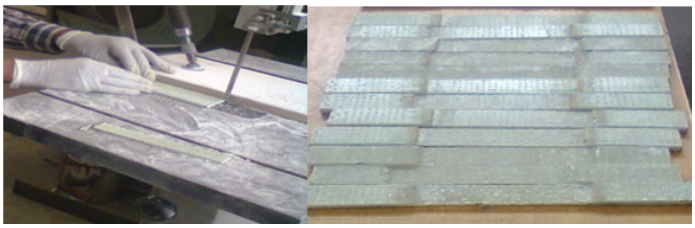


Figure 2 Composite specimens prepared for tensile and flexural tests.

Experimental Procedure

Tensile Test: In line with ASTM D3039, tensile tests were successfully carried out with computer controlled electro-hydraulic universal testing machine. Specimens with dimensions of 220 millimeters by 20 millimeters by 2.5 millimeters were subjected to a crosshead speed of 2 millimeters per minute until they failed. The tensile strength, modulus of elasticity and elongation at break were determined by analyzing the stress–strain data that was acquired.

Flexural Test: Following the guidelines of ASTM D7264, a three-point bending test was utilized in order to determine the flexural qualities. Specimens with dimensions of 150 millimeters by 20 millimeters by 4 millimeters were loaded at the mid-span until they fractured. The flexural strength of the specimens was determined by calculating the maximum load and the geometry of the specimens.

Analysis of the SEM: SEM was utilized in order to investigate fracture surfaces that were obtained from tensile and flexural tests. For the purpose of determining failure mechanisms such as fiber pull-out, matrix cracking, voids, and interfacial debonding, as well as establishing a connection between microstructure and mechanical performance, the samples were golden-coated and subjected to analysis.

RESULT AND DISCUSSION

This section presents and discusses the findings that were obtained from the universal testing machine and the scanning electron microscope (SEM) evaluation for the three manufacturing processes.

Tensile Properties

Figure 3 illustrates the tensile properties of glass/epoxy laminates produced using hand lay-up, vacuum bagging, and Vacuum Assisted Resin Transfer Molding (VARTM) methods. The findings explicitly demonstrate that the fabrication method substantially influences the tensile properties of the composites.

The hand lay-up laminates demonstrated the lowest tensile strength at 280 MPa, but vacuum bagging enhanced the tensile strength to 330 MPa. The maximum tensile strength achieved for the VARTM laminates was 444.49 MPa, in line with the previous literatures (Rydarowski and Koziol 2015). The enhancement in tensile strength for vacuum-assisted procedures is primarily due to superior laminate consolidation, enhanced fiber wetting, and less void content. During the hand lay-up procedure, uneven resin distribution and trapped air bubbles serve as locations of stress concentration, leading to premature failure under tensile loading.

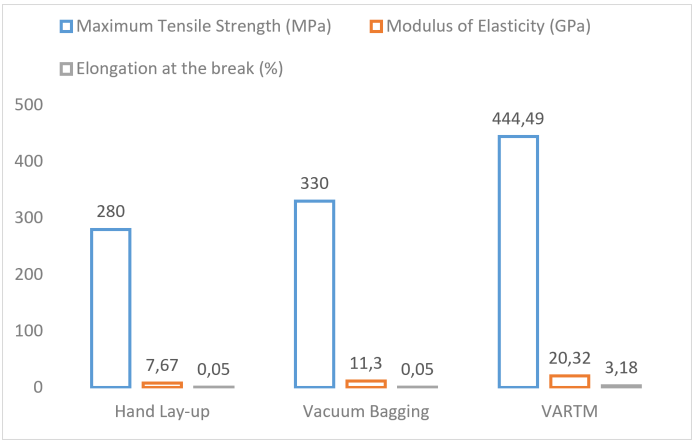


Figure 3 Tensile properties of glass/Epoxy laminate fabricated using Hand Layup, Vacuum Bagging and VARTM techniques

The modulus of elasticity also augmented with manufacturing quality. The hand lay-up specimens exhibited a modulus of 7.67 GPa, while vacuum bagging marginally elevated the modulus

to 11.3 GPa. The VARTM laminates demonstrated the greatest stiffness, with a modulus of 20.32 GPa, signifying enhanced load transfer between the fiber and matrix attributable to superior interfacial bonding and optimal resin impregnation.

The elongation at break was markedly affected by the manufacturing process. Both manual lay-up and vacuum bagging laminates demonstrated low elongation values of roughly 0.05%, indicating brittle failure behavior attributed to voids and inadequate fiber–matrix adhesion. Conversely, the VARTM laminates exhibited a significantly greater elongation at break of 3.18%, signifying enhanced ductility and postponed crack propagation attributable to superior laminate quality.

Flexural Properties

Figure 4 illustrates the flexural characteristics of glass/epoxy laminates produced using manual lay-up, vacuum bagging, and VARTM manufacturing methods. The findings indicate that the production technique substantially affects the flexural properties of the composites.

The hand lay-up laminates demonstrated a flexural strength of 407 MPa, but the vacuum bagging technique marginally enhanced the flexural strength to 435 MPa. The VARTM laminates attained the highest flexural strength, measuring 560 MPa. The higher flexural performance of the VARTM composites is due to optimized resin flow, superior fiber impregnation, greater laminate consolidation, and less void content. The diminished flexural strength in the hand lay-up laminates is primarily attributed to uneven resin distribution and the existence of voids, which compromise the laminate's load-bearing capacity during bending.

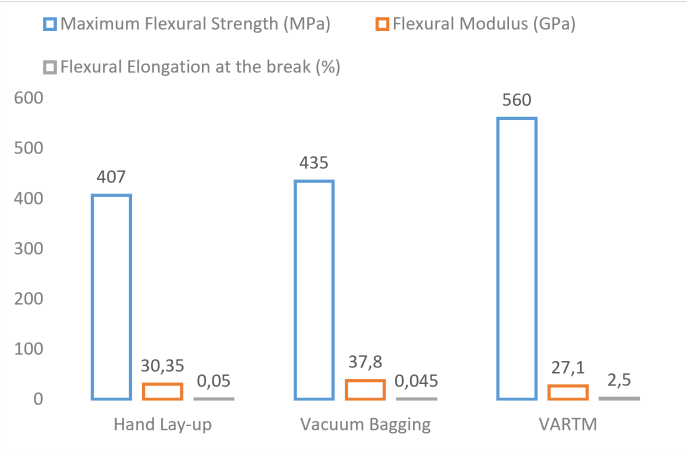


Figure 4 Flexural properties of glass/epoxy laminate fabricated using hand lay-up, vacuum bagging, and VARTM techniques.

The flexural modulus values fluctuated according to the manufacturing procedure. The vacuum bagging laminates exhibited the maximum flexural modulus at 37.8 GPa, whereas the hand lay-up laminates demonstrated a modulus of 30.35 GPa. The VARTM laminates demonstrated a flexural modulus of 27.1 GPa. While VARTM yielded the greatest flexural strength, the somewhat reduced modulus may correlate with enhanced ductility and a more uniform stress distribution within the laminate structure.

The flexural elongation at break underscores the impact of manufacturing quality on deformation characteristics. The manual lay-up and vacuum bagging laminates demonstrated minimal elongation values of around 0.05% and 0.045%, respectively, signifying relatively brittle fracture characteristics. Conversely, the VARTM laminates exhibited a much greater elongation at break of 2.5%, indicating enhanced flexibility and crack propagation resistance attributable to superior fiber–matrix interfacial bonding and diminished internal flaws.

Failure Analysis and Morphological Observations

Failure analysis showed significant differences in fracture morphology among the three manufacturing techniques, as depicted in Figure 5. The hand lay-up laminates exhibited extensive matrix cracking, fiber pull-out, delamination, and uneven fracture surfaces. These defects are associated with higher void content and non-uniform resin distribution. The vacuum bagging laminates showed improved laminate integrity with reduced delamination and better fiber–matrix adhesion. The VARTM laminates demonstrated comparatively uniform fracture surfaces and gradual failure mechanisms.

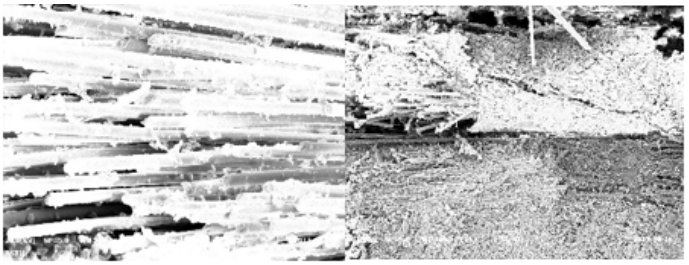


Figure 5 SEM image of the sample after test.

CONCLUSION

This study examined the tensile and flexural properties of glass/epoxy laminates made by manual lay-up, vacuum bagging, and VARTM. Experimental results showed that manufacturing technique greatly affects composite mechanical performance. VARTM laminates had the highest tensile (444.49 MPa) and flexural (560 MPa) strengths compared to manual lay-up and vacuum bagging. Tensile and flexural elongation at break improved with VARTM, suggesting ductility and crack resistance. Improved resin impregnation, laminate consolidation, fiber–matrix interfacial bonding, and void content are the key reasons. The vacuum bagging method had intermediate mechanical qualities and reduced porosity and laminate quality, outperforming manual lay-up. Due to non-uniform resin dispersion, entrapped air, and insufficient interfacial bonding, hand-laid laminates had the lowest tensile and flexural performance. The results show that vacuum-assisted manufacturing improves glass/epoxy composite mechanical behavior. Thus, structural applications demanding excellent tensile and flexural performance, durability, and laminate quality should use VARTM.

Ethical Standard

The author have no relevant financial or non-financial interests to disclose.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declares no conflict of interest.

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