International Journal of Engineering and Information Systems (IJEAIS)
ISSN: 2643-640X
Vol. 9 Issue 10 October - 2025, Pages: 71-76

Impact and Flexural Performance of E-glass/Epoxy Composites Fabricated via VARTM

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***ABSTRACT-**The development of lightweight and high-strength fiber-reinforced polymer composites has gained significant attention in structural engineering applications, including aerospace, marine, and automotive sectors. This study focuses on the fabrication and mechanical characterization of unidirectional E-glass/epoxy composites produced by Vacuum-Assisted Resin Transfer Molding (VARTM). Impact and flexural behaviors were experimentally investigated using standardized ASTM methods. Drop-weight impact tests were carried out at energies of 10, 20, and 30 J, while three-point bending tests evaluated flexural strength and modulus. The findings showed that increasing impact energy enhanced absorbed energy but also promoted matrix cracking and delamination. The flexural performance exhibited high stiffness and consistency across specimens, confirming the reliability of VARTM for E-glass/epoxy systems.*

Keywords E-glass/epoxy composites, VARTM, low-velocity impact, flexural strength, laminate fabrication, fiber-reinforced polymer, mechanical characterization, drop-weight impact, resin transfer molding, structural composites.

1. INTRODUCTION

Fiber-reinforced polymer (FRP) composites have emerged as essential materials in modern engineering due to their high specific strength, corrosion resistance, and fatigue durability [1–3]. Among these, E-glass fibers are the most widely used reinforcement type owing to their good mechanical properties, low cost, and processability [4,5]. When impregnated with thermosetting epoxy resin, they form strong interfacial bonding that enhances structural integrity and dimensional stability [6,7]. The epoxy resin system offers excellent adhesion, chemical resistance, and thermal stability, making it the preferred matrix for aerospace and automotive composite components [8,9]. Mechanical properties such as tensile strength, impact energy absorption, and flexural modulus are directly affected by fiber orientation, fiber volume fraction, and processing parameters [10–12].

COMPOSITE MANUFACTURING TECHNIQUES

Several manufacturing routes exist for fabricating FRP laminates, including hand lay-up, compression molding, and resin transfer molding (RTM). However, the **Vacuum-Assisted Resin Transfer Molding (VARTM)** method provides key advantages such as low cost, uniform resin infusion, reduced void content, and scalability for large parts [13]..The quality of VARTM composites is strongly dependent on parameters such as resin viscosity, vacuum pressure, and curing cycle observed that curing at elevated temperatures enhances the glass transition temperature (Tg) and stiffness of epoxy-based composites. The resulting fiber–matrix interaction plays a crucial role in determining the laminate's ability to withstand impact and bending stresses .

IMPACT AND FLEXURAL BEHAVIOR

Impact resistance is a critical property for composites subjected to dynamic loading. Low-velocity impacts, such as tool drops or debris strikes, can cause internal damage like delamination and matrix cracking without visible surface failure. According to Abrade, impact energy and velocity significantly influence the deformation and energy absorption pattern. Studies on E-glass/epoxy composites revealed that increasing impact energy results in larger damaged areas and reduced residual strength. Flexural performance, on the other hand, provides insight into the laminate's stiffness and load-bearing capability under bending. Previous studies have shown that unidirectional laminates exhibit higher flexural modulus compared to cross-ply configurations due to better fiber alignment].] reported that the span-to-thickness ratio and loading speed can influence the apparent modulus and failure strain.
This study addresses a gap in the literature by correlating both impact and flexural behaviors for VARTM-fabricated E-glass/epoxy laminates.

2. RESEARCH SIGNIFICANCE AND GAP

Despite the extensive research on FRP composites, limited work has integrated the correlation between impact energy absorption and flexural response in unidirectional E-glass/epoxy laminates fabricated using the VARTM technique. This study contributes to:

- Establishing a direct relationship between impact energy levels and resulting flexural stiffness.
- Providing verified experimental data on VARTM-fabricated E-glass/epoxy composites cured in multi-stage thermal cycles.
- Supporting the use of VARTM for cost-effective and high-quality structural composite fabrication.

3. MATERIALS AND METHODS

3.1 Materials

Reinforcement: E-glass unidirectional (UD) fiber (SWANCOR® 2511-1 A/BS).
Matrix system: Epoxy resin (Type JC02A) and hardener (Type JC02C), mixed at a ratio of 100:80.

Table 1. Material properties of E-glass fibers.

Property	Value
Tensile strength (MPa)	67–80
Tensile modulus (MPa)	2700–3500
Elongation (%)	4.5–8.5
Flexural strength (MPa)	110–140
Flexural modulus (MPa)	2800–3600
Tg (°C)	80–90
HDT (°C)	72–82

Table 2. Properties of epoxy resin and hardener system.

Property	Value
Elastic modulus (MPa)	2500
Poisson ratio	0.3
Density (g/cm³)	1.8
Yield strain (MPa)	100

3.2 Composite Fabrication

Fabrication was carried out using **VARTM**. Two unidirectional plies $[90]_2$ were stacked and impregnated with epoxy under vacuum.
Curing schedule:

- 2 h at 90°C
- 1 h at 110°C
- 4 h at 130°C

After curing, laminates were cut into specimens according to ASTM standards.

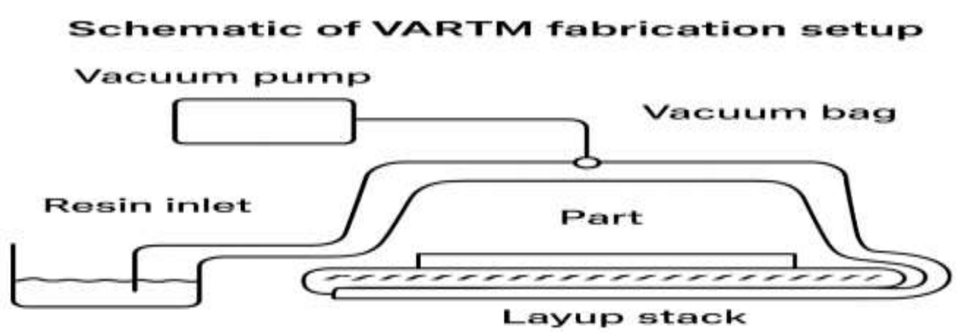

Figure 1. Schematic of the VARTM fabrication setup

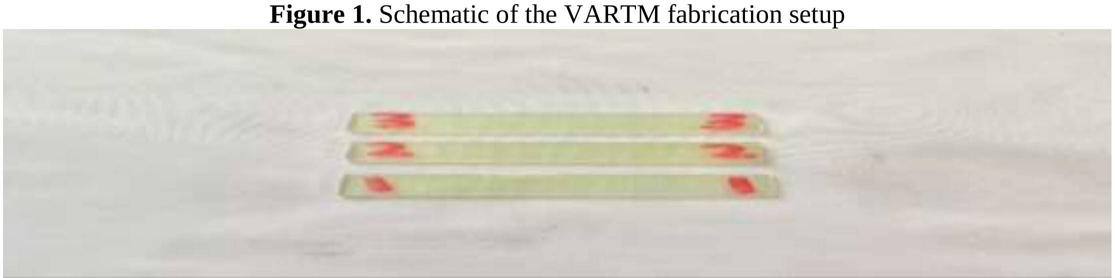

Figure 2. Cured E-glass/epoxy laminate before machining.

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3.3 Testing Procedures

A. Drop-Weight Impact Test

- Standard: ASTM D7136 [30]
- Equipment: Instron Dynatup 9250HV
- Specimen size: 150 × 100 mm
- Indenter mass: 12.3 kg
- Impact energies: 10, 20, and 30 J
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Table 3. Drop-weight impact parameters.

Specimen No	Energy (J)	Speed (m/s)	Height (m)	Mass (kg)
Specimen **1**	30	2.2086	0.2489	12.3
Specimen **2**	20	1.8033	0.1659	12.3
Specimen **3**	10	1.2751	0.0829	12.3

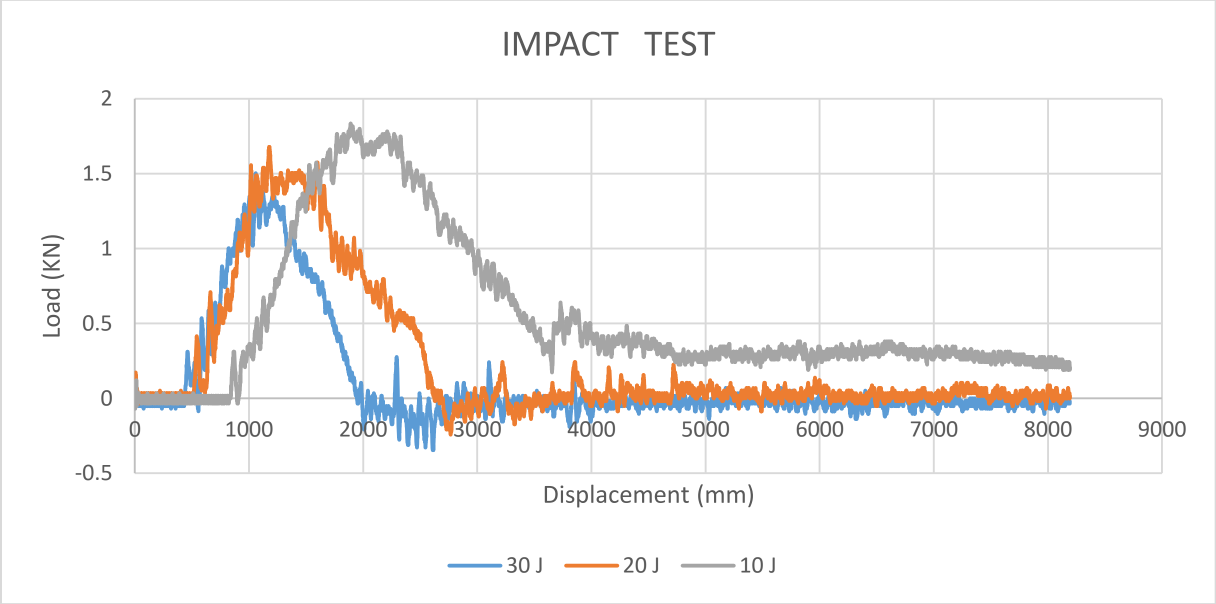

Figure 3. Load–Displacement curves for 10 J, 20 J, and 30 J impacts.

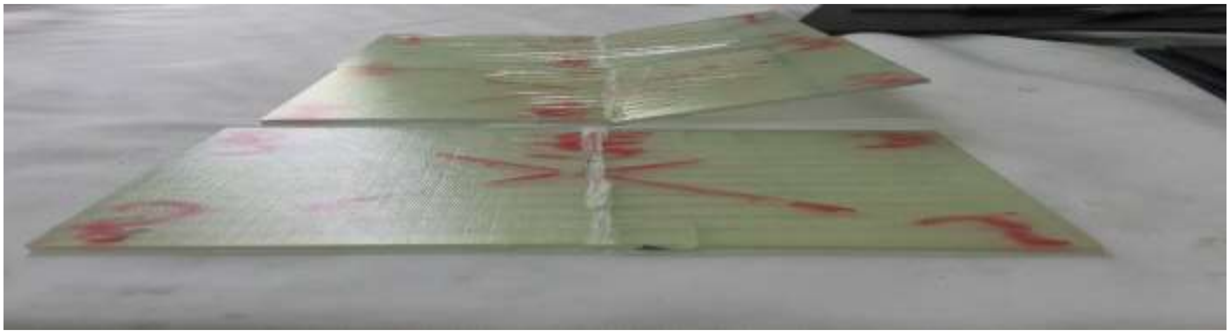

Figure 4. Photographs of specimens after impact showing visible surface indentation.

B. Flexural Test

- Standard: ASTM D7264
- Equipment: Instron 5967 AVE
- Span-to-thickness ratio: 16:1
- Test speed: 1 mm/min
- Specimen dimensions: 57.6 × 13 mm

$$\sigma_F = \frac{3pL}{2bd^2}$$

Where:

$$E_F = \frac{L^3 m}{4bd^3}$$

- σ_F = Flexural Strength (Mpa)
- E_F = Flexural Secant Modulus
- p=the peak applied force (N)
- L = support span, mm
- b= width of beam, mm
- d= thickness of beam, mm

Table 4. Flexural properties.

Specimen	σF (MPa)	EF (GPa)
Specimen **1**	763.8	15.0
Specimen **2**	948.8	15.6
Specimen **3**	758.6	18.8

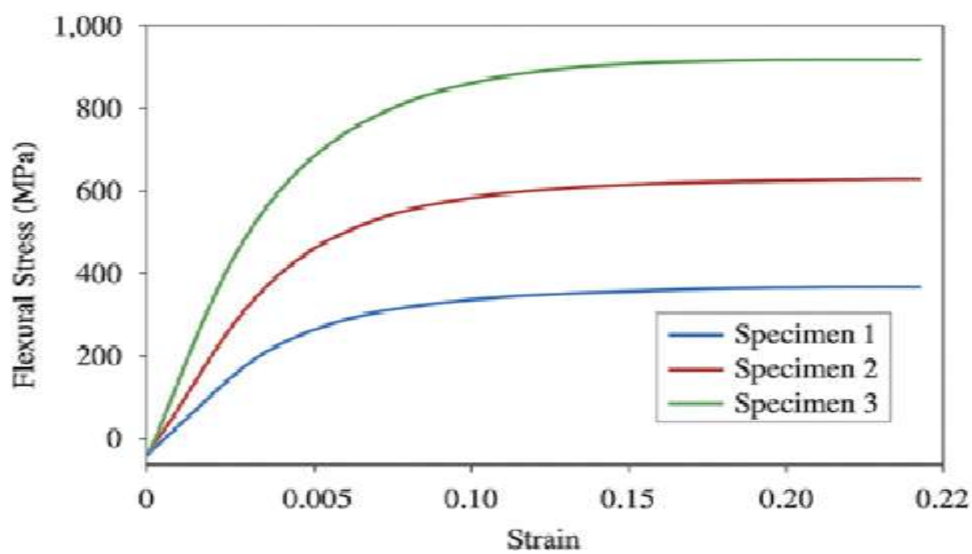

Figure.5 Stress Strain Curve

4. Results and Discussion

4.1 Impact Behavior

The impact response exhibited a typical rising and descending load–displacement pattern (Figure 3). The 30 J specimen absorbed more energy, indicating higher deformation and internal delamination. At 10 J, minor surface indentation and negligible matrix cracking were observed (Figure 2).

4.2 Flexural Performance

Flexural results (Table 4, Figure 5) demonstrated consistent stiffness and load-bearing ability. The highest flexural strength of 948.8 MPa and modulus of 18.8 GPa indicated efficient fiber alignment and resin impregnation

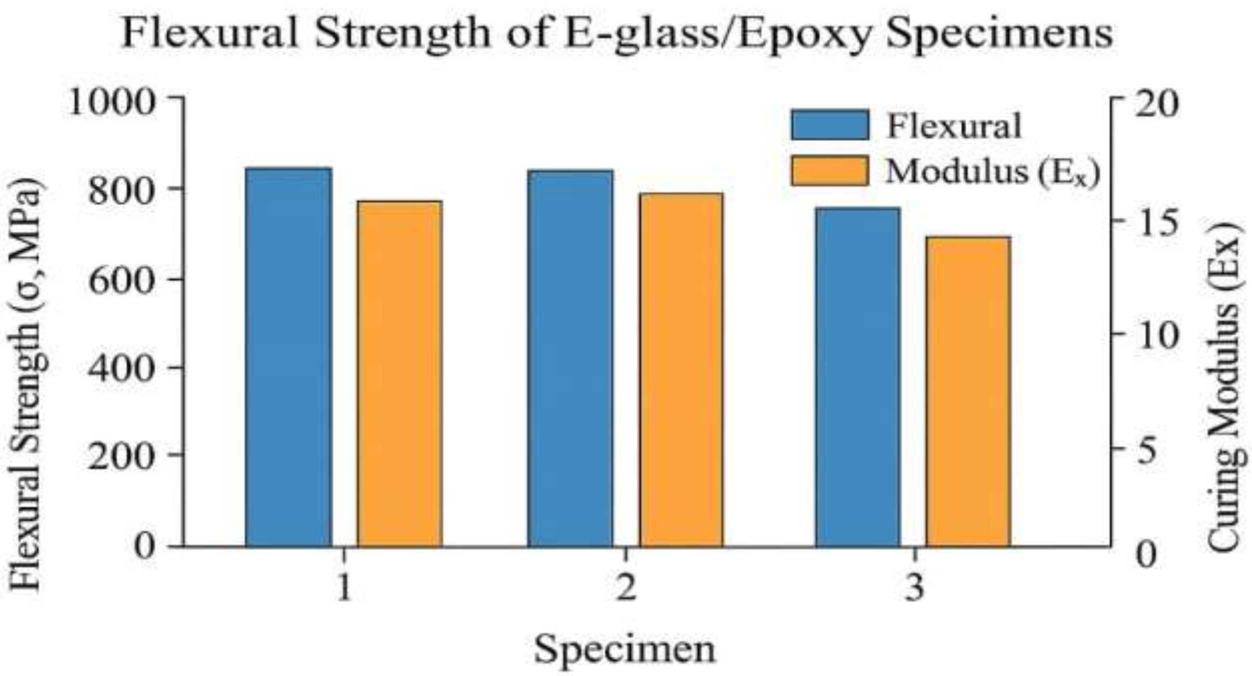

Figure 6. Comparison of flexural strength and modulus among specimens.

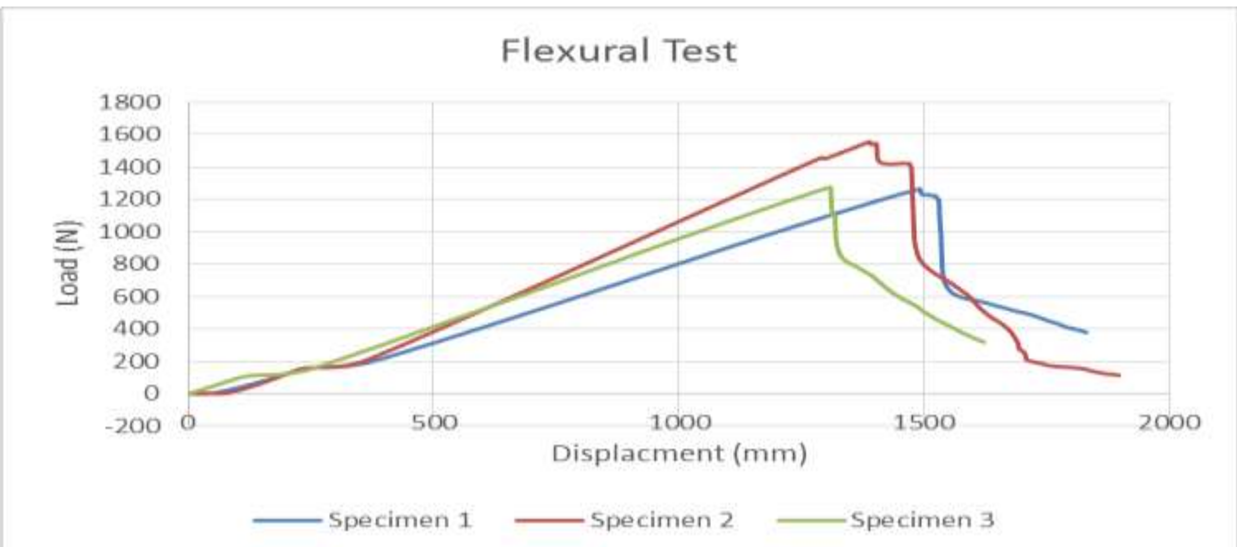

Figure7. Flexural Test

4.3 Correlation between Impact and Flexural Behavior

The specimens that absorbed more impact energy showed slightly reduced flexural stiffness, suggesting matrix degradation under high energy impact. This inverse relationship confirms damage accumulation, as reported in related FRP studies

5. Conclusion

Unidirectional E-glass/epoxy laminates fabricated via VARTM exhibited high mechanical integrity, excellent flexural stiffness, and reliable impact tolerance. The results confirm that:

- Impact energy directly affects internal damage and deformation.

- Flexural strength remains stable across specimens with minimal variation.
- The VARTM method effectively produces void-free, high-quality laminates suitable for structural applications.
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