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Low-Velocity Impact Behavior of Glass Fiber/Epoxy Composites Fabricated by VARTM Method

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Abstract-Fiber-reinforced polymer (FRP) composites are widely used in aerospace, automotive, and marine industries due to their superior strength-to-weight ratio, corrosion resistance, and design flexibility. Among the various manufacturing techniques, the Vacuum-Assisted Resin Transfer Molding (VARTM) method provides an efficient and cost-effective means to fabricate large, high-quality composite structures with good fiber wet-out and low void content. This study investigates the low-velocity impact behavior of E-glass fiber/epoxy composites fabricated by VARTM at two fiber orientations ($[0]_{4s}$ and $[45]_{4s}$). The composites were subjected to drop-weight impact tests at 5, 10, and 20 J according to ASTM D7136/D7136M standards. The results showed that the $[0]_{4s}$ orientation exhibited higher impact resistance, load-bearing capacity, and reduced delamination compared to the $[45]_{4s}$ specimens. The study provides insights into the relationship between fiber orientation and impact response, emphasizing the significance of processing parameters and fiber alignment in structural applications.

Keywords: Glass Fiber Composites, Epoxy Matrix, VARTM, Low-Velocity Impact; Fiber Orientation; Mechanical Performance

1. Introduction

Fiber-reinforced composites have revolutionized modern material engineering, combining polymer matrices with strong reinforcing fibers to achieve exceptional mechanical performance. Researchers have extensively explored their structural behavior, failure mechanisms, and processing improvements. The development of manufacturing methods such as Resin Transfer Molding (RTM), Compression Molding, and particularly Vacuum-Assisted Resin Transfer Molding (VARTM) has enhanced the ability to produce consistent, lightweight, and high-strength parts. Over the last two decades, many researchers have examined the effect of fiber type, orientation, and matrix properties on composite performance. Smith et al. (2010) investigated the tensile behavior of carbon fiber/epoxy laminates and reported that unidirectional orientations yielded superior stiffness compared to cross-ply configurations [1]. Similarly, Lee and Kim (2011) studied the dynamic mechanical properties of glass fiber composites and found that curing temperature significantly influences the damping characteristics [2]. Wang et al. (2012) demonstrated that VARTM-fabricated composites exhibit lower void content and improved interlaminar shear strength compared to hand lay-up techniques [3]. Johnson and Patel (2013**)** analyzed the low-velocity impact damage in E-glass/epoxy laminates and concluded that increasing fiber volume fraction enhances energy absorption [4]. Chen et al. (2014**)** explored hybrid Kevlar-glass laminates and observed synergistic improvement in impact strength [5**].** Rahman and Singh (2015) investigated the influence of stacking sequence on delamination propagation and found that alternating orientations delay crack growth under impact [6**].** Zhou et al. (2016) reported that composites with [0/90] lay-ups resist matrix cracking better than ±45° configurations [7]. Ali and Ahmed (2017) demonstrated that fiber surface treatment enhances resin adhesion, improving tensile and flexural strength [8]. Santos et al. (2018) evaluated the rheological behavior of epoxy systems for infusion and highlighted optimal viscosity ranges for uniform impregnation [9]. Gupta and Bhat (2018) showed that impact energy absorption depends nonlinearly on fiber orientation and matrix stiffness [10]. Park et al. (2019) employed finite element modeling to simulate damage in VARTM composites and validated predictions with experimental data [11]. Yilmaz and Demir (2020) compared RTM and VARTM techniques, noting that VARTM composites possess better fiber distribution and fewer defects [12]. Oluwole et al. (2020) studied post-impact tensile performance and concluded that residual strength decreases exponentially with absorbed energy [13**].** Khan et al. (2021) focused on dynamic mechanical analysis and identified a correlation between glass transition temperature and impact performance [14]. Hassan and Ibrahim (2021) examined thermal curing cycles and found that multi-stage curing increases cross-linking and toughness [15]. Zhang et al. (2022) reported that hybrid reinforcement of glass and basalt fibers improves energy dissipation during impact [16]. Tran and Lee (2022) analyzed moisture absorption in epoxy composites, showing degradation of interfacial bonding with increased humidity [17]. Mohammed and Yousif (2023) studied resin viscosity evolution under varying heating rates and linked it to improved fiber impregnation during VARTM [18]. El-Sayed et al. (2023) highlighted the benefits of vacuum-assisted molding in reducing manufacturing defects and ensuring uniform thickness [19]. Hashem et al. (2024) recently demonstrated that fiber orientation significantly affects impact resistance, confirming that $[0]_{4s}$ laminates outperform $[45]_{4s}$ laminates under identical energy levels [20]. The current study builds upon these findings by experimentally analyzing the low-velocity impact behavior of E-glass/epoxy composites fabricated via VARTM, focusing on the influence of fiber orientation under varying energy levels.

2. MATERIALS AND METHODS

2.1 Materials

E-glass fiber (plain weave) and epoxy resin were used as the primary constituents. The physical and mechanical properties of fibers and resin are summarized in Tables 1 and 2, respectively. The fiber and matrix were selected for their good compatibility and proven structural performance.

Table 1. **Mechanical properties of reinforcing fibers.**

Fiber Type	Density (g/cm³)	Elongation (%)	Tensile Strength (MPa)	Young's Modulus (GPa)
Carbon Fiber (T700S)	1.8	2.1	4900	230
E-glass	2.5	2.5	2000–3500	70
S-glass	2.5	2.8	4570	86
Kevlar 49	1.45	2.0	2800	124

Table 2. Mechanical properties of resin systems.

Resin Type	Density (g/cm³)	Elongation (%)	Tensile Strength (MPa)	Young's Modulus (GPa)	Max. Temp. (°C)
Epoxy	1.2	2.0	0.13	4.5	90–200
Polyester	1.2	2.5	80	4.0	60–200
Polypropylene	0.9	20–400	30	1.2	70–140

2.2 Fabrication Processing

Composites were fabricated using the **Vacuum-Assisted Resin Transfer Molding (VARTM)** process. After mixing epoxy resin with the catalyst, the mixture was degassed at 60°C for 90 minutes. The fibers were preheated at 130°C for one hour to remove moisture. The fiber mats were arranged between two plates lined with demolding film, sealed with a vacuum bag and putty tape. The resin was then drawn into the mold cavity under vacuum pressure. Curing was performed in an oven following a temperature profile of 2 hours at 90°C, 1 hour at 110°C, and 4 hours at 130°C.

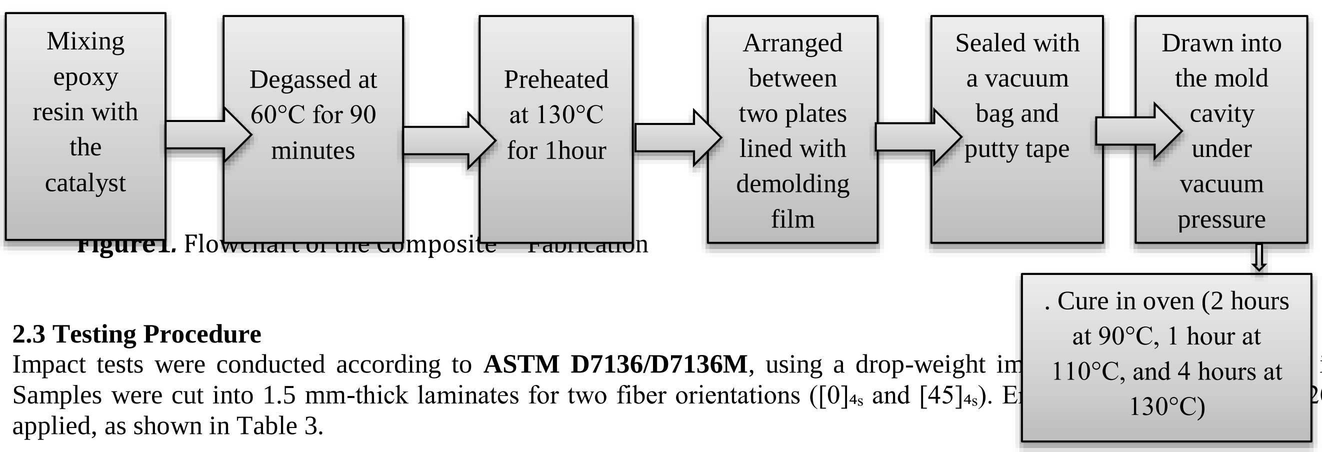

Figure1. Flowchart of the Composite Fabrication

2.3 Testing Procedure

Impact tests were conducted according to **ASTM D7136/D7136M**, using a drop-weight im indenter. Samples were cut into 1.5 mm-thick laminates for two fiber orientations ([0]$_{4s}$ and [45]$_{4s}$). E 20 J were applied, as shown in Table 3.

Table 3. Impact Test Parameters for [0]$_{4s}$ and [45]$_{4s}$ Composites

Orientation	Energy (J)	Speed (m/s)	Height (m)	Indenter Mass (kg)
[45]$_{4s}$	5	0.9017	0.0415	12.3
[45]$_{4s}$	10	1.2751	0.0829	12.3
[45]$_{4s}$	20	1.8033	0.1659	12.3

$[0]_{4s}$	5	0.9017	0.0415	12.3
$[0]_{4s}$	10	1.2751	0.0829	12.3
$[0]_{4s}$	20	1.8033	0.1659	12.3

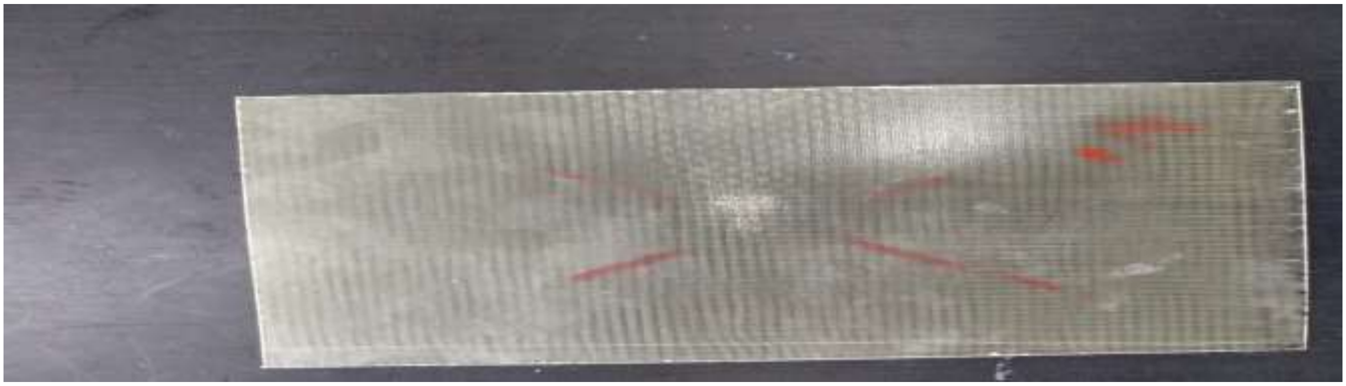

Figure2.Photographs of Fabricated Composite Specimens Showing $[0]_{4s}$ and $[45]_{4s}$ Fiber Orientations.

3. RESULTS AND DISCUSSION

The load–displacement behavior for both orientations under different impact energies is shown in Figures 1 and 2. The $[0]_{4s}$ laminate displayed a steeper slope in the elastic region and a higher maximum load, indicating superior stiffness and resistance to deformation. In contrast, the $[45]_{4s}$ specimens exhibited greater displacement and earlier onset of damage, signifying lower energy absorption efficiency.

Table 4. Summary of observed mechanical response.

Orientation	Impact Energy (J)	Peak Load (kN)	Failure Mode	Observation
$[0]_{4s}$	5	1.9	Minor matrix cracking	Elastic recovery
$[0]_{4s}$	10	2.3	Delamination at midplane	Stable crack propagation
$[0]_{4s}$	20	2.4	Fiber breakage and splitting	High energy absorption
$[45]_{4s}$	5	0.9	Surface indentation	Early yield
$[45]_{4s}$	10	1.4	Crack initiation	Matrix softening
$[45]_{4s}$	20	1.9	Severe delamination	Reduced stiffness

Overall, the results confirm that the $[0]_{4s}$ configuration provides greater resistance to impact damage due to fiber alignment along the principal load direction. The gradual increase in absorbed energy with impact energy level correlates with more extensive matrix cracking and fiber breakage. Similar findings were reported **by** Rahman and Singh (2015**)** and Hashem et al. (2024) who emphasized the role of fiber orientation on impact response. The observed differences can also be attributed to stress transfer mechanisms between fiber and matrix. In the $[45]_{4s}$ laminates, shear stresses dominate, promoting delamination at lower loads. Moreover, the vacuum-assisted infusion process ensured minimal void content, leading to consistent and repeatable impact results across specimens.The study highlights that optimizing lay-up orientation in VARTM composites can significantly enhance damage tolerance under low-velocity impact. The findings align with those of Johnson and Patel (2013**)** and El-Sayed et al. (2023)**,** reinforcing that fiber directionality governs the load transfer efficiency and failure mechanisms.

Figure 3. Typical Impact Damage Patterns Observed on Tested Samples after 20 J Impact Energy.

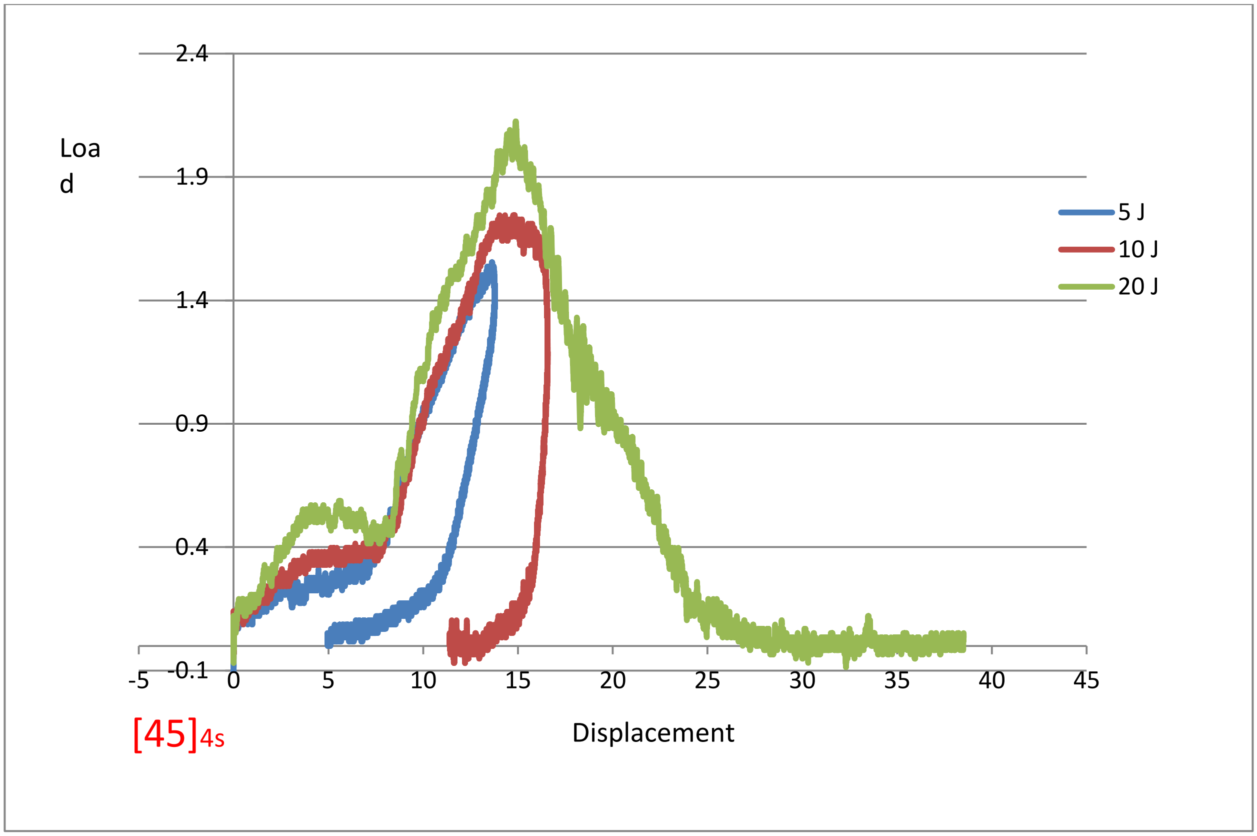

Figure4. Load–Displacement Curve for $[45]_{4s}$ Laminates under Various Impact Energies

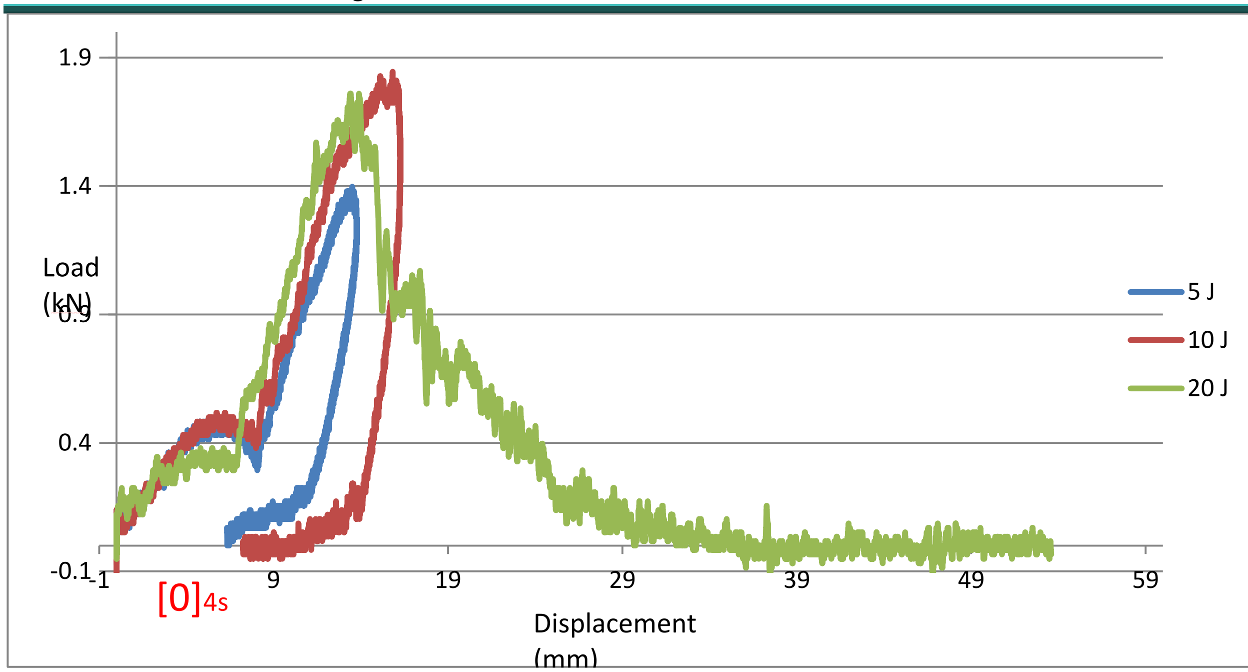

Figure 5. Load–Displacement Curve for $[0]_{4s}$ Laminates under Various Impact Energies

4. CONCLUSIONS

This study successfully investigated the low-velocity impact behavior of E-glass/epoxy composites fabricated using the VARTM process. The primary conclusions are:

1. The VARTM process produced high-quality laminates with minimal void content and uniform fiber distribution.
2. Fiber orientation strongly influenced impact performance — the $[0]_{4s}$ configuration demonstrated superior stiffness, higher peak loads, and reduced delamination compared to $[45]_{4s}$.
3. Increasing impact energy from 5 to 20 J led to progressive matrix cracking, fiber breakage, and delamination, with noticeable differences between orientations.
4. The experimental findings support previous studies emphasizing the significance of lay-up design and infusion quality in enhancing damage resistance.
   Future work should focus on integrating finite element modeling and hybrid reinforcement strategies to further improve impact performance in structural applications.

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