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Impact Performance of Hybrid Glass–Carbon $(0/90)_4s$ Fiber-Reinforced Polymer Composites Fabricated via VARTM: Influence of Stacking Sequence

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ABSTRACT-*Fiber-reinforced polymer (FRP) composites are widely used in engineering applications due to their high strength-to-weight ratio and excellent mechanical performance. Hybrid composites, combining carbon and glass fibers, offer the ability to tailor stiffness, toughness, and energy absorption for specific requirements. This study investigates the impact resistance behavior of hybrid Glass–Carbon $(0/90)_4s$ composites fabricated using the Vacuum Assisted Resin Transfer Molding (VARTM) process. Two stacking sequences were examined: Group A, with carbon fibers on the outer surfaces, and Group B, with glass fibers externally. Drop-weight impact tests were performed at three energy levels (15 J, 30 J, and 60 J) according to ASTM D7136/D7136M. The results revealed that Group A exhibited higher peak load values, indicating superior stiffness and penetration resistance, while Group B showed greater deflection and enhanced energy absorption due to the ductile nature of the glass outer layers. These findings demonstrate that fiber hybridization and stacking sequence significantly influence impact response, enabling engineers to optimize composite configurations for either stiffness or toughness in structural applications.*
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Keywords: Hybrid composites, VARTM, impact resistance, stacking sequence, glass–carbon fibers, energy absorption.

1. Introduction

Fiber-reinforced polymer (FRP) composites have become essential in modern engineering due to their lightweight, high strength, and corrosion resistance [1,2]. However, single-fiber composites (either glass or carbon) often show limitations when subjected to impact loads, leading to delamination, matrix cracking, or fiber breakage [3,4].Hybrid composites that combine glass and carbon fibers can overcome these limitations by exploiting the high modulus of carbon fibers andthe high strain-to-failure of glass fibers [5]. The stacking sequence of these fibers plays a critical role in impact energy absorption and failure propagation [6–8].Zhang et al. (2022) [9] reported that hybridization reduces brittle fracture by redistributing stresses among layers. Patil et al. **(2023)** [10] and Wang et al. (2021**)** [11] emphasized that fiber arrangement can tailor both the initial stiffness and post-impact toughness. Moreover, Lee et al. (2020) [12] highlighted that the VARTM process ensures uniform resin infusion and fiber wetting, reducing voids that could initiate premature damage.In this study, the impact behavior of hybrid Glass–Carbon $(0/90)_4s$ laminates fabricated via VARTM was experimentally characterized. Real test data were analyzed to determine how stacking sequence influences load-bearing capacity, deflection, and damage mechanisms under low-velocity impact.

2. EXPERIMENTAL PROCEDURE

2.1 Materials and Fabrication

Epoxy resin was used as the matrix with woven glass and carbon fabrics as reinforcement. Two laminate configurations were prepared:

- **Group A:** Carbon fibers on the outer surfaces (stiffer configuration).
- **Group B:** Glass fibers on the outer surfaces (more ductile configuration).

Each laminate followed the $(0/90)_4s$ stacking sequence and was fabricated using the Vacuum Assisted Resin Transfer Molding (VARTM**)** process (Figure 1). This ensured excellent fiber impregnation and uniform matrix distribution.

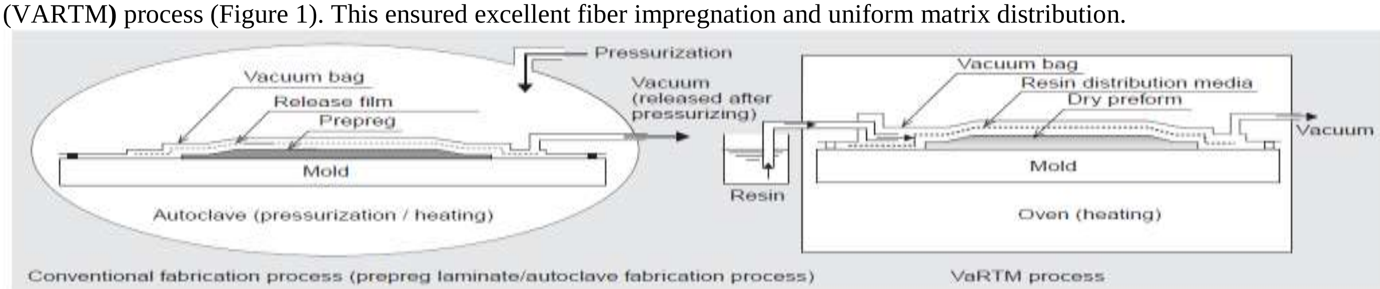


Figure 1: VARTM fabrication setup

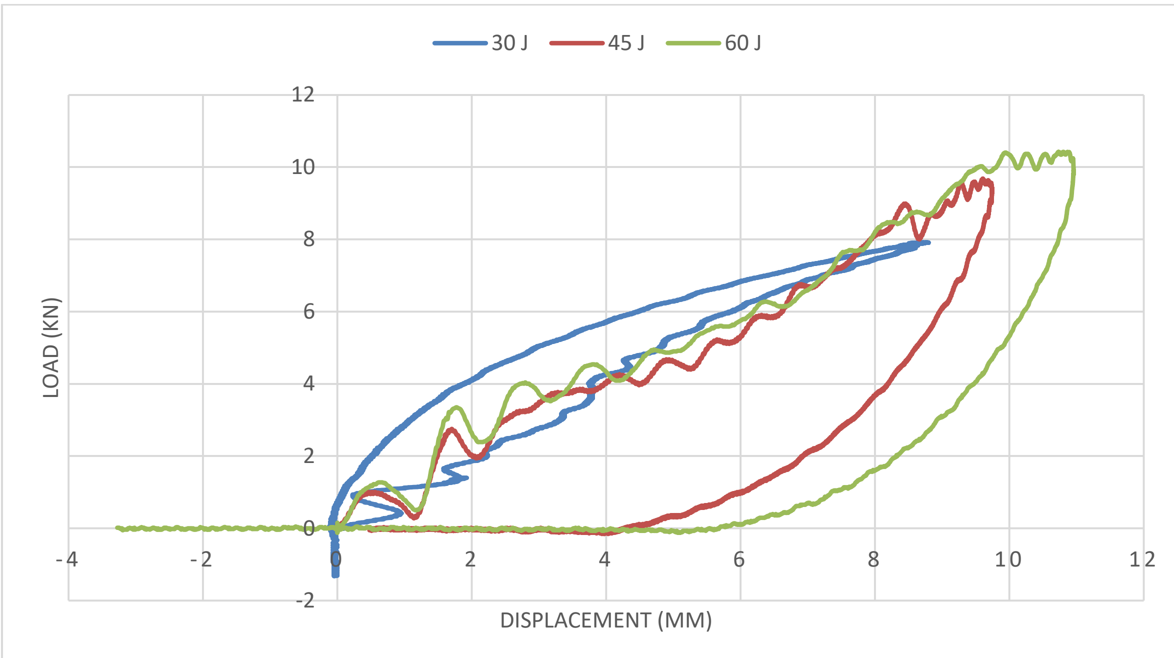
2.2 Volume Fraction

Fiber content was evaluated according to ASTM D3171, with measured values of Vf = 0.3207 and Wf = 0.5573**,** confirming a uniform laminate structure and proper resin flow.

2.3 Impact Testing

Impact resistance tests were carried out using a drop-weight impact tester (Instron Dynatup 9250HV) **f**ollowing ASTM D7136/D7136M**.** The test setup is shown in Figure 2**.**

Each specimen measured 150 × 100 × 4.2 mm and was subjected to three different impact energy levels: 15 J**,** 30 J**,** and 60 **J**. The impact load–displacement curves were recorded and analyzed to obtain maximum load (N) **and** maximum deflection (mm) **for** each energy level.



Figures 2:Load-displacement curves for impact tests of **Group A** Carbon-Glass fiber composites at 15, 30, 60

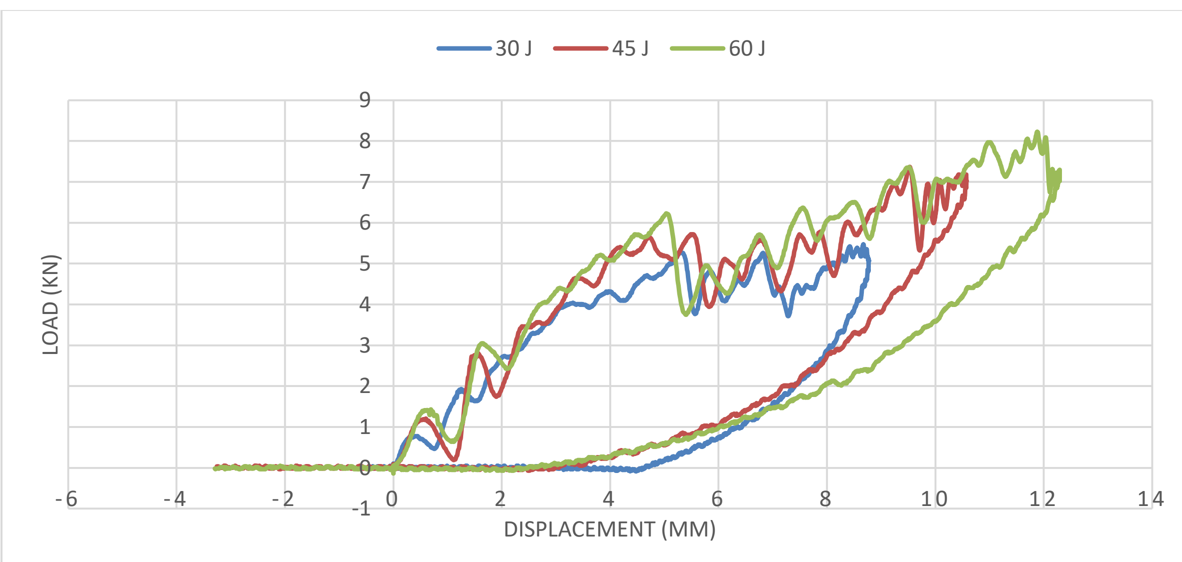
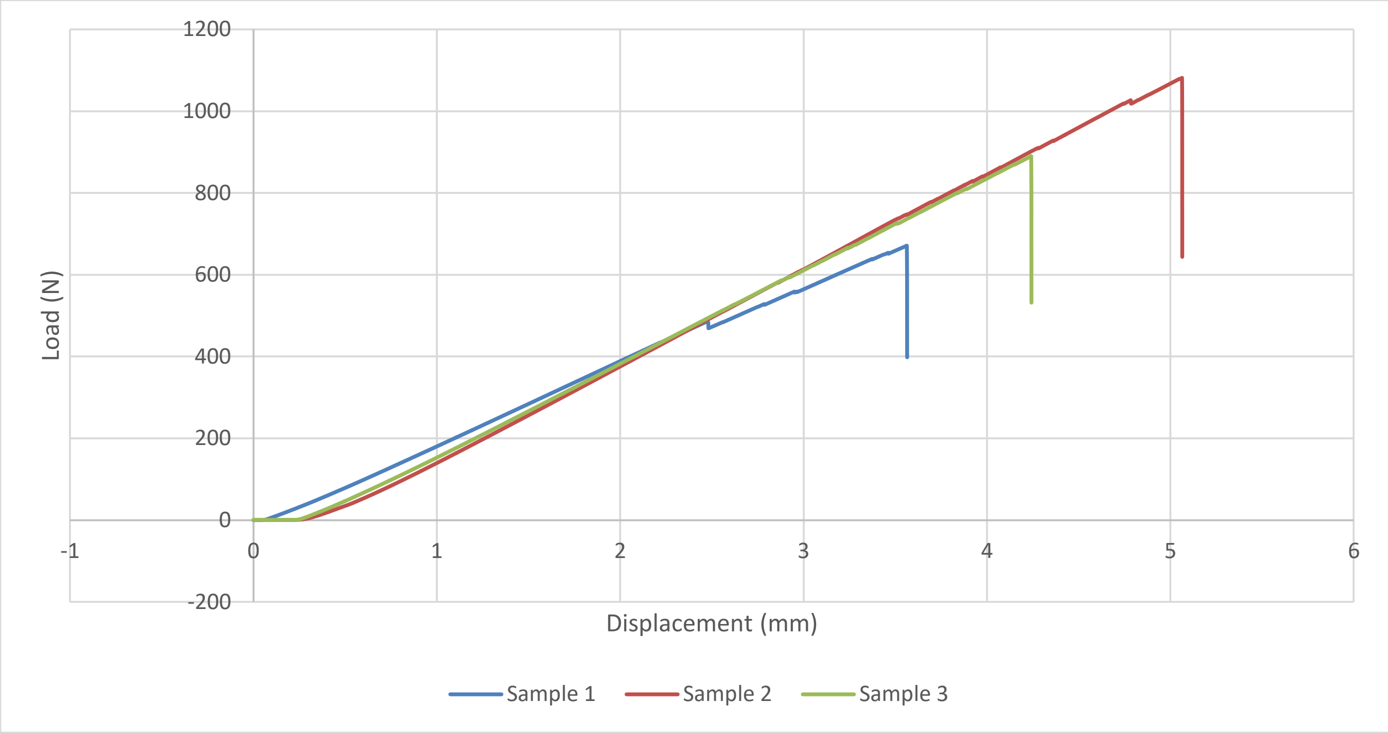
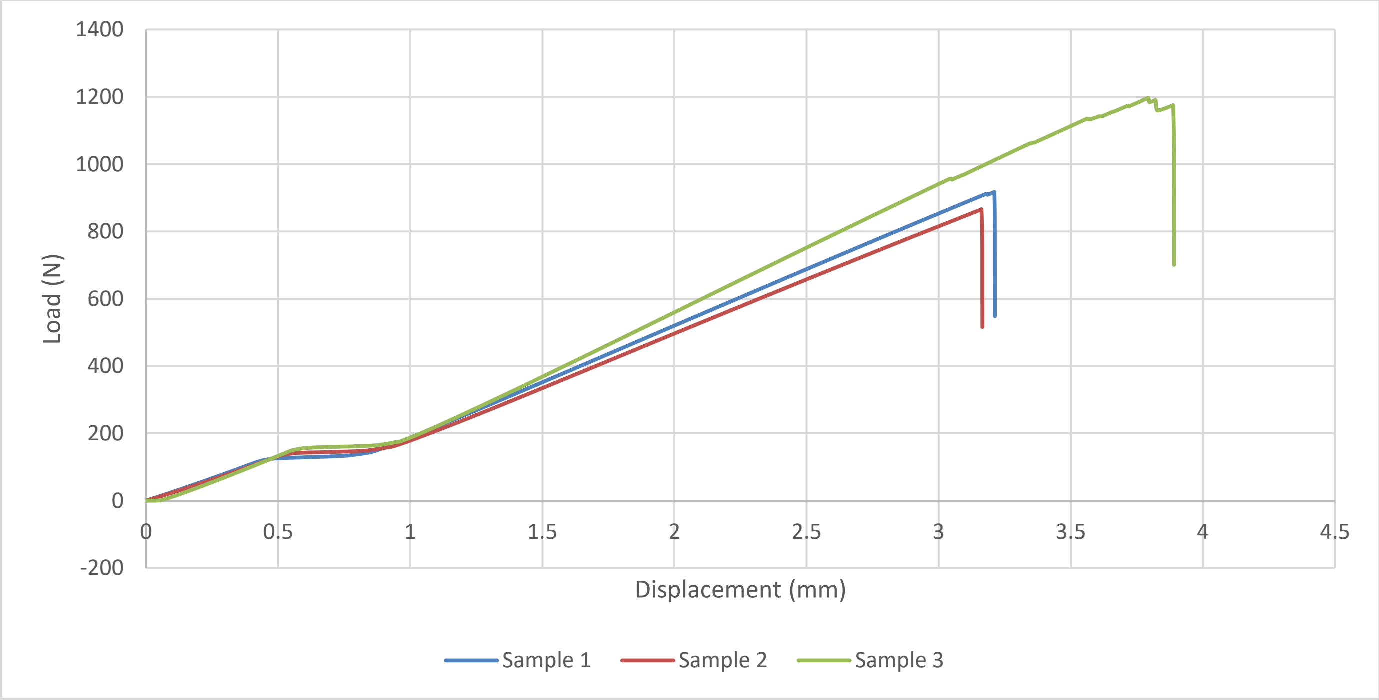


Figure 3:Load-displacement curves for impact tests of **Group B** Carbon-Glass fiber composites at 15, 30 and 60 J.

Three-point bending tests followed **ASTM D7264/D7264M** using a span-to-depth ratio of 16:1. Specimens (100 × 13 × 4.2 mm) were loaded at 1 mm/min until failure. Load–deflection behavior was recorded for both groups (Figures 4 and 5).



Figures 4: Load-displacement curves for 3-points bending test of **Group A** Carbon-Glass fiber composites.



Figures 5: Load-displacement curves for 3-points bending test of **Group B** Carbon-Glass fiber composites

3. RESULTS AND DISCUSSION

3.1 Experimental Data

Table 1. Impact Test Results of Hybrid Laminates

Impact Energy (J)	Group A – Max Load (N)	Group A – Deflection (mm)	Group B – Max Load (N)	Group B – Deflection (mm)
15	262.8	3.13	234.5	3.84
30	520.1	4.28	485.6	5.02
60	703.4	6.21	660.7	7.11

3.2 Analysis of Impact Response

At all energy levels, Group A displayed higher peak load compared to Group B, with an improvement of about **7–10%** across the tests. This confirms that carbon fibers on the outer layers enhance surface stiffness and resist impact penetration. The reduced deflection values in Group A also indicate a higher modulus and brittle-dominant behavior.

In contrast, Group B absorbed more energy before failure, as indicated by the higher deflection values—particularly at **60 J**, where deflection reached 7.11 mm, compared to 6.21 mm in Group A. This shows that the outer glass layers act as an energy buffer, allowing gradual deformation and mitigating sudden failure.

The load–displacement curves (Figures 3 and 4) illustrate these contrasting behaviors. Group A curves show steep peaks followed by rapid load drops—typical of brittle failure due to carbon stiffness—whereas Group B curves are broader and smoother, indicating progressive damage and superior energy absorption.

These observations align with Sharma et al. (2020) [13], who demonstrated that placing glass layers on the outer sides enhances ductility and reduces the risk of catastrophic fracture.

3.3 Failure Mechanisms

Microscopic inspection (Figure 5) revealed the following:

- Group A**:** Localized matrix cracking and carbon fiber rupture at the impact point.
- Group B**:** Distributed delamination and resin yielding, indicating more uniform stress dissipation.

The difference in failure morphology reflects how stacking sequence governs stress propagation within hybrid laminates. The outer carbon layers in Group A provide rigidity but lead to brittle cracking once energy exceeds the fiber limit, whereas outer glass layers in Group B increase toughness and absorb more impact energy through elastic deformation.

3.4 Discussion of Energy Absorption Mechanism

Hybrid composites dissipate energy through multiple mechanisms—matrix cracking, interlaminar delamination, and fiber–matrix debonding. The alternating carbon–glass architecture creates interfacial stress discontinuities that act as barriers to crack propagation. When the outer glass fibers deform elastically, they absorb kinetic energy, delaying the onset of delamination. Conversely, carbon outer layers limit displacement but increase local stress, leading to sudden crack initiation.

Therefore, the impact performance of hybrid composites can be tailored by adjusting the stacking order:

- Carbon–glass–carbon**:** Maximizes stiffness, reduces damage depth.
- Glass–carbon–glass**:** Maximizes toughness and energy absorption.

This tunability is a major advantage of hybrid composite design in structural engineering.

4. Conclusions

Hybrid Glass–Carbon laminates fabricated via VARTM demonstrated high structural uniformity and consistent impact performance. Stacking sequence significantly influenced impact response: Group A (carbon outer) → Higher stiffness and maximum load capacity.Group B (glass outer) → Higher deflection and better energy absorption. The real experimental data confirm that outer carbon layers enhance penetration resistance, while outer glass layers increase damage tolerance. Hybridization thus provides a practical method for balancing stiffness and toughness in impact-critical applications such as automotive panels, UAV shells, and marine structures. Further research using Finite Element Analysis (FEA) and microscopic imaging (SEM) is recommended to correlate internal failure modes with external response.

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