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Development of a Side Door Composite Impact Beam for the Automotive Industry

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Abstract

The automobile industry has been searching for vehicles that use less energy and emit fewer pollutants, which has resulted in a high demand for fuel-efficient vehicles. Because of their higher strength-to-weight ratio compared to traditional steel, using fiber-reinforcement composite materials in automobile bodies has emerged as the most effective strategy for improving fuel efficiency while maintaining safety standards. This research paper examined the utilization of fiber-reinforced composite materials in car bodies to meet the increasing consumer demand for fuel-efficient and eco-friendly vehicles. It particularly focused on a carbon-aramid fiber-reinforced composite impact beam for passenger car side door impact protection. Despite the encouraging prospects of the carbon-aramid fiber-reinforced beam, the research uncovered substantial defects in the fabrication process, resulting in diminished load-bearing capacity and energy absorption. As a result, the beam was unsuccessful in three-point bending tests. This was accomplished by using an I cross-section design with varying thickness because of the higher area moment of inertia. Vacuum-assisted resin transfer molding (VARTM) manufacturing process was used and the finished beam underwent to three-point bending tests.

Keywords

Side-Door Impact Beam, Impact Energy Absorption, Carbon-Aramid Reinforcement, VARTM

1. Introduction

Side-door impact beams are used in passenger car door panels to protect passengers from side impacts. The door's durability is essential in preventing side-impact collisions [1] [2]. The shape and mounting configuration of the side door impact beam is depicted (**Figure 1**). Impact beams must have remarkable static strength and impact energy absorption capabilities in order to achieve the requisite standards for strength and absorption. In side door impact beams, composite materials are used instead of standard steel because they are preferred not only for lightweight structure but also to provide the desired qualities of high strength and toughness. They are interdependent on parameters like material, diameter and thickness of the side impact beam [3] [4]. To increase the efficiency of the beam suitable material selection is necessary. The conventional way to manufacture side door impact beams was by press-forming high-strength steel sheet, which has been replaced recently by lightweight composite beams. The significance of composites in the automotive sectors and the expanding usage of natural fibers in these industries are shown by researchers' studies of composite materials and their uses.

Automobile manufacturers currently prioritize weight reduction as a crucial priority due to the global movement towards laws on fuel efficiency and petrol emissions in passenger vehicles. Fiber-reinforced composite materials are becoming increasingly prevalent in the aerospace and automotive industries, due in significant measure to their amazing combination of high specific strength (strength per unit of density) and specific stiffness (stiffness per unit of density). These materials also exhibit exceptional impact resistance. Composites are now used in more industries attributed to their reduced cost, including those that produce sports equipment, leisure goods, machinery and vehicle constructions. According to reports from the US and Germany, plastics and composites are extensively employed in numerous automotive applications such as car body panels, bumper systems, flexible components, trims, driveshafts and transparent parts. Over time, there has been a continuous effort to decrease the weight of cars, to enhance fuel efficiency. However, the aim of increased fuel efficiency has occasionally resulted in compromised vehicle safety [5] [6] [7] [8]. To address

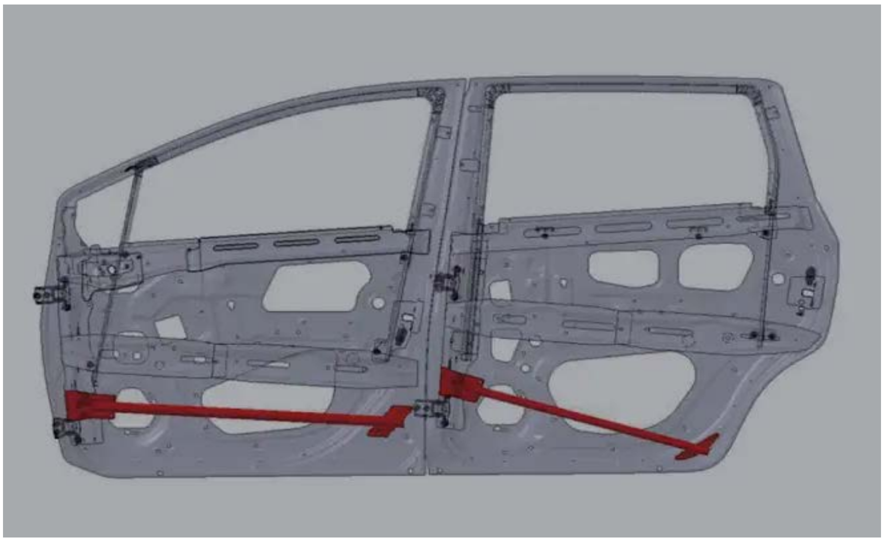

Figure 1. Shape and mounting configuration of the side door impact beam.

this challenge and achieve better fuel efficiency without sacrificing safety, a viable solution lies in utilizing fiber-reinforced composite materials for the car's body structure. Due to their greater specific strength compared to conventional metals, using fiber-reinforced composite materials, such as carbon fiber and aramid fiber, offers a compelling advantage. [9] [10] [11]. A notable property of these composites is their capacity to tolerate large pressures while retaining their structural integrity. These composite materials can be used to build the car body, allowing for increased fuel efficiency without sacrificing safety. This is mostly due to the outstanding energy absorption properties of fiber-reinforced composites, especially in impact situations. A car composed of such composite materials would efficiently absorb and diffuse the impact energy in the unfortunate event of an accident, lowering the likelihood of injury to occupants. In conclusion, using fiber-reinforced composite materials in the car's body not only improves fuel efficiency but also dramatically reduces damage to people's bodies in collisions. This strategy strikes a compromise between safety and fuel efficiency, providing a potential new direction in the quest for more environmentally friendly and secure transportation. Carbon and glass fiber-reinforced polymer composites can directly reduce the weight of the parts of an automobile, such as the engine block and chassis, which reduces the vehicle's fuel consumption. These materials can be used to replace conventional steel & cast-iron components with lightweight composite materials like Mg & Al metal matrix composite. Automobiles can carry more complex emission control systems, safety equipment, and integrated electrical systems without adding to the total weight of the vehicle by using light composites. It can improve fuel economy while reducing exhaust emissions.

The results highlight that the glass-fiber-epoxy composite impact beam has 30% weight reduction as compared to high-strength steel impact beam based on the static bending tests [12] [13] [14]. Moreover, some researchers also took metal-composites hybrid and examined square hollow aluminum beam with laminated carbon fiber reinforced polymer (CFRP). They discovered that at 2.5 mm thickness, CFRP laminates absorbed 25% more energy compared to aluminum alloy alone. Apart from metal and alloy materials, researches were performed on polymer composite material application on side door impact beam. The whole component may be replaced with composites or steel parts may be integrated into one composite structure depending on the structure and fiber orientation.

Therefore, a glass fiber reinforced polypropylene composite and a hybrid composite of sugar palm fiber and glass fiber were used to fabricate side door impact beams. The beams were fabricated using the hot compression molding technique. This means that the hybrid composite theoretically possesses the capacity to absorb energy higher than the steel structure by 61.9%. Furthermore, the hybrid composite beam allowed a weight reduction up to 59.2% while the glass fiber reinforced PP composite beam recorded a reduced weight of 54.5% when compared with a conventional steel beam. In conclusion, the hybrid composite side door impact beam performed better in terms of weight reduction and energy absorption as compared to a traditional steel beam. **Table 1** shows the comparison of material properties. The selection of manufacturing process plays a vital role in complex and large composite parts. Vacuum assisted resin transfer molding (VARTM) process is one of the open mold composite manufacturing processes which are highly used for manufacturing of large composite parts. The capacity of composite materials to absorb energy provides a special combination of reduced weight and enhanced crashworthiness of the vehicle structures [15] [16] [17]. The interfacial bonding qualities between the reinforcing fiber and matrix of FRPs were explored not only under static loading but also under dynamic loading to improve the impact energy absorption of unidirectional CFRP by sub-micron glass fiber into its matrix [18]. Previous study, the manufacturing development of laminated carbon fiber reinforcement thermoplastic polymer (CFRP) specimens, showed significant improvement in mechanical properties in comparison with existing thermoplastic composites [19].

2. Experimental

2.1. Materials

2.1.1. Carbon-Aramid Fiber

In this study, a hybrid plain weave 3 k carbon-Kevlar cloth (**Figure 2**) was used as a fiber reinforcement due to carbon provides high levels of stiffness and strength, whereas aramid provides huge impact, abrasion and fracture resistance than that of conventional steel (*i.e.*, high-strength steel). This cloth comes with thickness of 0.3 mm and areal weight 188 g/m^2. The fabric is made up of two sets of fibers positioned at 0 degrees (to the warp) and 90 degrees (perpendicular, to the warp) respectively. This arrangement is referred to as a 1 × 1 weave pattern, where the fiber orientation is specified as [0˚/90˚]. The properties of carbon and aramid fibers indicates in **Table 2**.

Table 1. Comparison of material properties for different materials [2].

Material properties	Aluminum alloy	High-strength steel	Carbon fiber	Aramid fiber
Young's modulus E, (GPa)	70	210	"225 - 240"	"58 - 80"
Density, (g/cm^3)	2.7	7.8	"1.75 - 1.8"	"1.39 - 1.44"
Yield strength Y, (MPa)	276	470	-	1240
Tensile strength, (MPa)	"70 - 700"	"500 - 2000"	"4 - 4.8"	"2.8 - 3.0"

Table 2. Properties of carbon and aramid fibers.

Material	Density (g/cm^3)	Tensile strength (GPa)	Modulus of elasticity (GPa)	Specific tensile strength (GPa)
Carbon fiber (high-strength)	"1.75 - 1.8"	"2.7 - 3.5"	"225 - 240"	"1.5 - 2.0"
Aramid	"1.45 - 1.47"	"2.8 - 3.4"	"117 - 186"	"1.9 - 2.3"

Figure 2. Hybrid Carbon-Kevlar fabric.

2.1.2. Epoxy Resin

IN2 is an industry-standard epoxy infusion resin. As shown in **Table 3** its low viscosity, clear UV stable appearance, excellent mechanical properties with slow hardener speed make it the first choice for high performance resin infusion, especially in conjunction with high-performance reinforcements such as carbon fiber and Kevlar. It is crucial that you strictly observe the recommended mixing ratios by precisely weighing the resin and hardener using appropriate scales. Mix the resin and hardener thoroughly until they are evenly combined, paying close attention to the walls and bottom of the mixing container. This system was mixed to a weight ratio of 100:30, resin to hardener.

2.2. VARTM Process

The selection of manufacturing process plays a vital role in complex and large composite parts. Large composite parts are frequently produced using the VARTM process, one of the open mold composite manufacturing methods. It operates at ambient temperature and atmospheric pressure. Therefore, it is controlled easily. The process parameters in this procedure are the volume fraction, compaction pressure, and component thickness variation.

The VARTM process consists of three steps:

Step 1: Molding Process—**Figure 3** Describes the consumables and equipment components necessary for the VARTM-process, as well as the various stages of the process. Initially, layers of fiber reinforcement are applied on a previously treated mold with a release agent to form the preform. **Table 4** represents the various compositions of the six distinct specimens. Peel ply is placed over the preform, allowing easy separation of the consumables from the part and creating a reasonable surface finish. Distribution media are arranged in a sequence manner and the use of a vacuum to assist in resin flow. Once the inlet and vent tubes are in location, as the mold is sealed with a vacuum bag sealed with sealant tape (also known as sticky tape). With the cavity sealed, the inlet is clamped and vacuum is applied to the vents, this stage being referred to here as

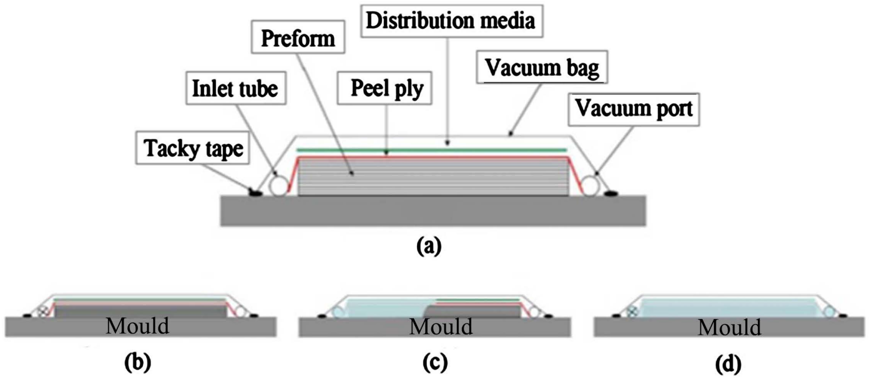

Figure 3. Schematic diagram of experimental setup for VARTM process. (a) Lay-up, (b) Pre-filling, (c) Filling, (d) Post-filling.

Table 3. Mechanical properties of epoxy resin.

Mechanical Properties		
Tensile strength	"63.5 - 73.5"	MPa
Flexural strength	"112 - 124"	Mpa
Elongation at break	"6.0 - 8.0"	%
Viscosity	325	mPa·s
Port life	90	Min
Initial cure time	24	Hr.
Density at 23˚C	"1.08 - 1.12"	g/ml
Hardness at 23˚C	"84.5 - 88.5"	Shore D/15

Table 4. Compositions for different specimens.

Specimen	Epoxy resin (wt-%)	Carbon-aramid (wt-%)
S01	70	30
S02	60	40
S11	50	50
S12	40	60
S21	30	70
S22	20	80

"pre-filling". At the end of pre-filling, the inlet is opened and the resin propagates through the preform. During the "filling stage", pressure inside the cavity depends on position and time. Within the impregnated portion of the preform the resin pressure varies from vacuum at the flow front to atmospheric pressure at the inlet. Once the preform is completely filled, either the inlet is clamped or inlet and vent port are directly connected to equilibrate resin pressure within the laminate. The "post-filling" stage involves removal of excess resin, and allows resin pressure and laminate thickness to equilibrate within the cavity [20].

Step 2: Demolding Process—After completing the solidification time, the consolidate materials are removed from the mold. The peel-ply helps for easy removal of the manufactured fabric composite component. The manufactured component put in the oven at 100-degree Celsius temperature for two hours which helps in complete curing of resin and solidified the manufactured component.

Step 3: Surface Finish to Manufactured Part—The boundary surface of the manufactured component is very uneven and rough therefore cutting and grinding tools are used for making smooth surface finish of the components [16].

Benefits:

1) Compared to other manufacturing techniques, it has a high fiber to resin ratio. The weighted percentage ranges from 60% to 80%.

2) Flexible in terms of mold tooling design and material selection.

3) Extremely popular for producing big composite parts with exceptional strength and dimension precision.

4) Very simple to use and took less time to cure.

5) It is possible to store the resin and hardener separately because they were just blended before the infusion.

6) It worked at air pressure, necessitating no additional external pressure.

Limitations:

1) Depending on the worker's experience and skills, the composite item may be damaged during vacuum leaking. Observation must continue throughout the infusion period.

2) The vacuum bagging side's surface polish is not as nice as the surface on the mold side.

3) Peel ply, sealant tape, and resin tubes are examples of consolidation materials that should be prepared individually every time because they are not reusable [16].

2.3. Methodology

2.3.1. Determination of a Suitable Cross-Section for the Side Door Impact Beam

During the early phases of the product's development and design process, it is crucial to consider and decide on other vital design criteria, such as the shape and thickness of cross-sections, in addition to the material choice. In this study, the I cross-section of a side-door impact beam was selected, because this geometry possesses the highest aerial moment of inertia (**Figure 4**).

2.3.2. Wood-Mold Preparation

A wood was used to create I-cross section double-sided molds to manufacture the composite part using the VARTM process. A wood is typically constructed by shaping wood material into the desired I cross-section profile, which serves as a structure for the final composite part (**Figure 5**). These molds consist of two

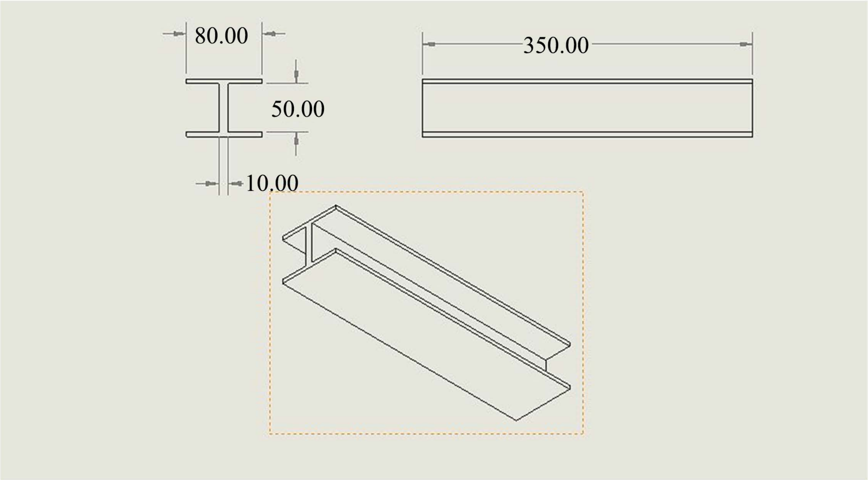

Figure 4. I cross-section type of the side door impact beam (all dimensions in millimeters).

Figure 5. Wooden mold.

halves that are placed on either side, enclosing it to create a cavity where the composite part will be formed. Once the resin has cured, the double-sided molds are separated, and the composite part is removed. The overall dimension of the beam is 70 mm × 60 mm × 350 mm.

2.3.3. Experimental Setup for the VARTM Process

The hybrid carbon-aramid fiber reinforcements were placed with a [0˚/90˚] stacking sequence. The fiber reinforcements have not been surfacing treated because different bonding agents impact the mechanical properties of the composite differently depending on the type of resin employed. On both sides of the fibers, peel ply was applied. The distribution media was placed on top of the peel ply to guarantee rapid and even distribution of resin over the fibers. The complete system is then placed in a vacuum bag, (**Figure 6**) depicts the way the full lay-up was put together. The processing phase consists of adjusting the vacuum bag's pressure due to air leakages can cause resin to improperly flow through the

Figure 6. Experimental setup for VARTM process.

mold and also lead to the formation of air bubbles. Before infusion, the high-performance low viscosity epoxy resin was well mixed with a suitable mixing stick for at least one minute. Furthermore, after finishing mixing in one container, then transferred the mixed resin to a second container and continued mixing with a new mixing stick. This eliminates the possibility of mistakenly using unmixed resin from the container's bottom or sides. After mixing the resin with the hardener, the resin is forced to move into the still-clamped inlet tube. Once the inlet was unclamped, the resin flowed through the distribution media and impregnated the hybrid carbon-aramid preform transversely. The preform was purposefully kept a little outside of the mold to absorb resin escaping from the outlet vent, allowing us to close the clamp. After the resin arrived at the end of the preform, the process ended and the specimen was cured for 24 hours at room temperature, followed by 3 hours at 100˚C.

2.4. Property Measurements

Flexural Tests

The side door impact composite beam was tested on a universal machine (flexural test) DIN EN ISO 178 with a three-point bending test (**Figure 7**). The bending test has great importance for the determination of parameters for polymer and composite materials. A load was supplied at the center of the specimen while it was being supported by a span, creating three-point bending at a test speed of 5 mm/min, and the flexural modulus was measured. The specimen length of 300 mm and with I cross-section was tested. The pre-load and speed of the flexural modulus were 1 N and 1 mm/min respectively.

3. Results and Discussion

3.1. Flexural Test Analysis: Deflection, Force, Young's Modulus, Moment of Inertia and Maximum Stress

1) Deflection Measurement: During the test the deflection of the specimen was recorded as 0.137 mm. This measurement indicates the amount of bending the specimen experienced under applied load.

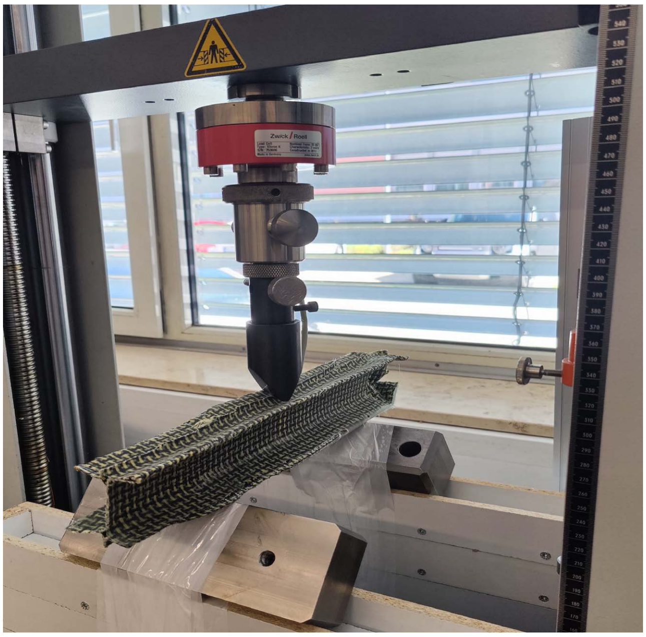

Figure 7. Three-point bending test (Flexural test).

$$\textbf{Deflection} \quad f_m = \frac{F_l^3}{48EIy} \tag{1}$$

$F = 10$ KN (applied load on the specimen)

$L = 64$ mm (span length)

$I = 43.08 \times 10^6$ mm^4 (moment of inertia)

$E = 0.920$ MPa

2) Maximum Stress: The test results indicated a recorded maximum stress of the specimen 5.26 MPa.

$$\textbf{Maximum Stress} \quad \sigma = \frac{F}{A} \tag{2}$$

$F = 10$ KN (applied load on the specimen)

$A = 1900$ mm^2

The specimen had significant flexibility when subjected to the given force, as evidenced by the 0.137 mm deflection that was obtained. This implies that the material is somewhat ductile and can deform under load without breaking. The calculated Young's modulus of 0.920 MPa sheds light on the rigidity of the material. It implies that the material is relatively compliant and may be appropriate for applications where some degree of flexibility is required. It also shows that the material has a comparatively low modulus of elasticity. The test results revealed that the specimen endured a maximum stress of 5.26 MPa, highlighting the critical value at which the material can withstand external force.

The specimen's 3-point bending test yielded crucial information on its deflection, applied force, Young's modulus, and moment of inertia at the Y-axis. The outcomes provided insight into the material's mechanical behavior and structural soundness, opening up the possibility of applications in numerous engineering specialties. To confirm the accuracy and dependability of the experimental results, additional examinations and comparisons with the body of literature are advised.

3.2. Comparative Evaluation of Composite Side Impact Beam with Steel and Aluminum

This study compares the deflection behavior of a composite side door impact beam to that of typical steel and aluminum beams under identical stress conditions. As Table 5 reveal that deflection varies significantly amongst materials, with the composite beam being less stiff than steel and aluminum. Steel is the most rigid alternative, although aluminum provides a good combination of strength and deflection. To provide maximum structural performance, material selection for specific applications should include these deflection qualities as well as aspects like weight, cost, and corrosion resistance.

3.3. Defects and Challenges of the VARTM Process

In this study, although the VARTM process had various advantages in composite manufacturing, such as cost-efficiency and reduced environmental impact, it was not without defects and obstacles. It was critical to address these challenges, in order to achieve consistent, high-quality composite products using VARTM technology.

One notable issue encountered was the formation of voids caused by fiber misalignment. This problem occurred when the reinforcing fibers deviated from their original arrangement during the manufacturing process. As a result, the composite part compaction was weakened, resulting in deformation in the final finished parts. Another significant defect in the VARTM process was maintaining uniform resin flow throughout the mold, especially in complex I cross-section geometry. Due to inadequate vacuum pressure inside the mold, non-uniform resin distribution occurred. As an outcome, the excess resin was absorbed from the inlet side. Furthermore, sustaining a consistent resin flow at the outlet side posed an additional hurdle. Such inconsistency resulted in the delamination composite structure and the formation of voids within the composite material, thereby dropping structure integrity. Moreover, the demolding procedure was difficult, particularly when dealing with enclosed molds and complex geometries. After-curing composite component extraction was frequently challenging due to excess resin accumulating at the entrance side.

Table 5. Compositions for different specimens.

Sr. No.	Beam	Cross-section	Young's modulus (GPa)	Load (KN)	Deflection (mm)
1.	Composite beam	I cross-section	0.92	10	0.137
2.	Steel	Circular	210	10	1.106×10^{-7}
3.	Aluminum	Circular	70	10	3.31×10^{-7}

4. Conclusions

This study created hybrid composites by reinforcing carbon-aramid fibers with epoxy resin using the VARTM process and experimenting with different compositions, in order to improve the strength and stiffness of a side door composite impact beam. This fabrication method proved to be both simple and cost-effective. Mechanical properties such as flexural strength and Young's modulus were examined. Furthermore, a comparative analysis was done between the mechanical properties of the composite and those of steel and aluminum materials.

The results showed a significant difference in deflection behavior between materials, with the composite beam having a lower rigidity than its steel and aluminum equivalents. Addressing these issues is critical for producing consistent and high-quality composite products using Vacuum Assisted Resin Transfer Molding (VARTM) technology. The VARTM fabrication method discovered major challenges in composite manufacturing. Void creation due to fiber misalignment, uneven resin flow in complex geometries, and vacuum pressure and resin distribution issues were among them. These concerns must be addressed for high-quality composites and process efficiency. Additional research, experimentation, and comparisons with existing literature are required to assess the correctness and dependability of the results obtained in this study.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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