

Mechanical Performance Assessment of Hybrid–FRP Laminates with a Carbon–Fiber Core Using Experimental and Numerical Approaches

Gopal Wadnere¹, Kiran Kaware², Mangesh Kotambkar³, Ankur Vasava⁴, Mayur Gitay⁴, Nandkishor M. Sawai^{5,*}

Abstract

The high strength-to-weight ratio, corrosion resistance and design flexibility of Fiber-reinforced polymer (FRP) composites have attracted considerable attention in aerospace, automotive and structural applications. This work presents an experimental and finite element study on the tensile and flexural behavior of epoxy-based hybrid–FRP laminates. Five laminate configurations were manufactured, including a unidirectional carbon fiber laminate and four hybrid laminates, Kevlar–Carbon–Kevlar (K/C/K), Glass–Carbon–Glass (G/C/G), Kevlar–Carbon–Glass (K/C/G), and Glass–Carbon–Kevlar (G/C/K). For all hybrid configurations, a six-ply carbon fiber core was placed in between Kevlar and/or glass fiber layers to evaluate the effect of fiber hybridization and stacking sequence on mechanical performance. The tensile and flexural properties were experimentally obtained according to the ASTM D3039 and ASTM D7264 standards, respectively. The material properties obtained were then used to build finite element models in Abaqus. Numerical simulations consisted of defining orthotropic materials, proper boundary conditions, mesh discretization, and nonlinear failure criteria. The accuracy of the models generated was assessed by comparing the predicted responses with the corresponding experimental results. The finite element method was found to be reliable and numerical results agreed very well with the experimental results. The carbon rich laminates showed improved tensile and flexural properties due to the exceptional stiffness and strength of the carbon fibers. The Kevlar and glass fiber layers improved the damage tolerance and structural integrity. The validated models are a reliable tool for the prediction of the behavior of hybrid composites. They allow to design lightweight high-performance structures with better mechanical efficiency.

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INTRODUCTION

Fiber reinforced polymer (FRP) composites are important engineering materials because of high strength to weight ratio, corrosion resistance, fatigue durability and design flexibility. These properties have led to their widespread use in aerospace, automotive, marine, defense and structural applications where weight reduction and superior mechanical performance are critical requirements. Epoxy based laminates reinforced with synthetic fibers have attracted great attention due to their excellent

mechanical properties and processing versatility among various polymer matrix composites. Composite components used in structural applications are often subjected to tensile and bending loads during service and tensile and flexural properties are thus among the most important parameters governing material selection, structural integrity and long-term reliability [1, 2]. The most common reinforcing fibers are carbon, glass and Kevlar fibers which have their own mechanical benefits. Carbon fibers possess a high stiffness, tensile strength and dimensional stability. They are generally used for load bearing applications where a high specific strength is required. Glass fibers are widely used because they have a good combination of strength, stiffness, chemical resistance and cost. The Kevlar fibers have high toughness, good energy absorption capability, and good crack propagation resistance. In contrast to the brittle fiber systems, Kevlar-reinforced composites generally show progressive failure mechanisms through fiber bridging, pull-out and energy dissipation processes, thus improving the damage tolerance and post-failure integrity [3, 4].

The hybridization of different fiber reinforcements in a single laminate has become an effective approach to combine the advantageous properties of the individual fibers while reducing their inherent limitations. Carbon–glass and carbon–Kevlar hybrid composites have received a great deal of research interest because they can simultaneously offer high stiffness, enhanced strength, improved impact resistance and better damage tolerance. The synergistic interaction among different fibers leads to more efficient stress distribution and crack-arrest mechanisms resulting in improved structural performance compared with single-fiber composites [3, 4]. Mechanical behavior of hybrid composites is highly dependent on laminate architecture, fiber volume fraction, stacking sequence and interfacial bonding characteristics. Tensile loading is mainly used to assess the axial load-bearing capacity, stiffness, ultimate strength and failure mechanism of composite laminates. Typical tensile failure modes are matrix cracking, fiber fracture, fiber pull-out and interlaminar delamination. On the contrary, flexural loading induces tensile, compressive and interlaminar shear stresses, and therefore, provides a more realistic description of the service conditions of structural elements. Thus, the flexural performance is more sensitive than the tensile performance to stacking sequence and layer arrangement [5, 6]. The glass fiber reinforced epoxy composites showed excellent tensile and flexural properties due to efficient transfer of applied loads between the matrix and reinforcing fibers. It has been shown in prior studies that the placement of high-stiffness fibers close to the outer surfaces of laminates greatly improves the flexural stiffness and the bending resistance. Similarly, the inclusion of Kevlar layers in hybrid laminates results in higher damage tolerance and retarded crack propagation. Carbon fibers significantly increase the stiffness and load carrying capacity of composite structures due to their high modulus and strength. Therefore, the use of carbon, glass and Kevlar fibers in optimized stacking sequences has a great potential for the development of light-weight and mechanically efficient structural materials [7–9].

Epoxy composites have been investigated by many researchers for the effect of hybridization and stacking sequence on their mechanical performance. Ekşi et al. [10] studied carbon–glass–aramid hybrid laminates and reported that tensile, flexural and impact properties were highly dependent on layer arrangement. Ishtiaq et al. [11] investigated glass–carbon–Kevlar hybrid laminates with different stacking sequences and showed that optimized arrangements can offer a good balance between mechanical strength, impact resistance and thermal stability. Saravanan et al. [12] tested epoxy laminates made of glass-, carbon-, Kevlar- and hybrid-fibers, and they reported that the carbon–fiber composites showed the highest tensile strength, whereas the Kevlar-based laminates exhibited the best impact resistance. T.G. et al. [13] showed that the combination of natural and synthetic fibers significantly improved the overall mechanical and environmental performance of epoxy composites. Wang et al. [14] studied carbon/Kevlar, carbon/glass and carbon/glass/Kevlar hybrid laminates and showed that considerable improvement in tensile strength and stiffness can be obtained through appropriate hybridization and optimization of stacking-sequence. Despite considerable progress in the development of hybrid-composite laminates, significant variability in the reported mechanical properties still exists due to variations in the fabrication methods, fiber architecture, curing conditions and laminate configurations. Moreover, the experimental characterization is mostly focused on most of

the published studies, with a relatively limited attention to validation of experimental results with reliable finite element modelling. The existence of numerical models, verified experimentally, is necessary for accurate prediction of the mechanical response of hybrid composite structures and for reduction of experimental trials at the design stage.

Although several studies have investigated carbon/glass, carbon/Kevlar, and glass/Kevlar hybrid laminates with different stacking sequences, most investigations focus on varying the entire laminate architecture or optimizing symmetric hybrid layups. Limited attention has been devoted to maintaining a constant carbon-rich structural core while systematically modifying only the outer reinforcing plies to isolate the influence of surface reinforcement on the tensile and flexural responses. In the present work, a six-ply carbon fiber core is retained in all hybrid configurations, whereas only the outer Kevlar and glass fiber layers are varied. This design strategy enables a direct assessment of how outer-layer hybridization affects load transfer, stress redistribution, stiffness, ductility, and failure mechanisms without changing the primary load-bearing carbon framework. Furthermore, the study combines comprehensive experimental characterization with validated finite element simulations, providing both physical understanding and a predictive numerical methodology for designing carbon-core hybrid-composite laminates for lightweight structural applications. The novelty of this work lies in maintaining a constant carbon-fiber structural core while systematically varying only the outer Kevlar and glass reinforcement layers, thereby isolating the effect of surface hybridization on the mechanical performance and enabling experimentally validated finite element predictions for optimized laminate design.

MATERIALS AND METHODOLOGY

Selection of Materials

Selected E-glass fabric, Carbon T300 fabric and Kevlar fabric were chosen to be used in the advanced hybrid composite applications due to their complementary mechanical, thermal and physical properties. The Carbon T300 fiber was selected because of its high tensile strength, high modulus, low density and excellent fatigue resistance, and is widely used in aerospace structures, automotive components, sporting goods and high-performance engineering applications. Kevlar fiber was selected because of its outstanding toughness, impact resistance and energy absorption capacity desirable for ballistic protection, aerospace panels, helmets and crash resistant structures. Woven E-glass fiber was added due to its good mechanical strength, corrosion resistance, electrical insulation properties and cost effectiveness, making it suitable for marine, automotive, wind energy and civil engineering applications. The selected reinforcement fibers were chosen to exploit their complementary mechanical characteristics. Carbon fiber serves as the primary load-bearing constituent because of its high specific stiffness and tensile strength. Kevlar fiber was incorporated to improve toughness, resistance to crack propagation, and energy absorption, whereas E-glass fiber was selected to enhance dimensional stability, compressive performance, and cost effectiveness. The combination of these three fibers provides an appropriate balance between stiffness, strength, damage tolerance, and manufacturing economy, making the laminate architecture suitable for lightweight engineering structures subjected to combined tensile and flexural loading.

The hybridization of these fibers makes it possible to develop composite laminates with a balanced combination of stiffness, strength, toughness, thermal stability and durability. Carbon fibers are used for structural stiffness, Kevlar fibers for damage tolerance and impact resistance, and E-glass fibers for surface durability and cost savings. This combination of these three fibers is thus very suitable for lightweight, high-performance structural applications with superior mechanical and environmental performance. The hybrid fiber reinforced polymer (FRP) composite laminates investigated in this work were manufactured by Vacuum-Assisted Resin Transfer Molding (VARTM) process. The reinforcement material used was of three types, woven E-glass fabric, carbon T300 fabric and Kevlar fabric of areal density 220 GSM. The main reinforcement was selected to be carbon fiber because of its high specific strength and stiffness whereas the addition of glass and kevlar fibers was to improve the structural integrity, damage tolerance and load redistribution capability. Table 1 shows the properties of the fibers.

Table 1. Properties of the fiber.

Property	Carbon T300 fiber	Kevlar fiber (aramid)	Woven E-glass fiber
Density (g/cm ³)	1.76	1.44	2.54.
Tensile Strength (MPa)	3500–3800	3000–3600	2000–3500.
Tensile Modulus (GPa)	230	70–130	72–85.
Elongation at Break (%)	1.5–1.8	2.5–4.0	3.0–5.0.
Specific Strength	Excellent	Excellent	Good.
Specific Stiffness	Excellent	Moderate	Good.
Impact Resistance	Moderate	Excellent	Good.
Fatigue Resistance	Excellent	Very Good	Good.

The hybrid-composite laminates were fabricated by Vacuum-Assisted Resin Transfer Molding (VARTM) process, because of its ability to produce high-quality composites with uniform resin distribution, excellent fiber wetting and low void content. In this process dry fiber layers were stacked in the desired stacking sequence, covered with a vacuum bag and impregnated with epoxy resin under vacuum pressure. The vacuum applied resulted in complete resin infusion and good consolidation of the laminate. VARTM was selected over conventional fabrication techniques, such as hand lay-up and compression molding, because of better process control, improved fiber-to-resin ratio and reduction in manufacturing defects. VARTM produces better mechanical properties than hand lay-up by reducing air entrapment and resin-rich regions. The quality of the laminate produced by an autoclave process is excellent, but the equipment is expensive and the operating cost is high. Thus, VARTM provides an optimal trade-off between quality of the laminate, manufacturing cost and process simplicity, making it a widely preferred method for fabrication of advanced polymer composite structures for applications in aerospace, automotive and marine industries. The overall laminate thickness was maintained at approximately 1.6 mm for all configurations to ensure consistent fiber volume fraction throughout the study. Since identical fabric areal density, ply count, manufacturing process, and resin infusion parameters were employed for all laminate configurations, the fiber volume fraction remained nearly constant, thereby ensuring that variations in mechanical performance could primarily be attributed to the stacking sequence and outer-layer hybridization rather than differences in fiber content. For this purpose, an epoxy resin system was used as a matrix material for composite fabrication. The epoxy resin system consists of YD-535 LV epoxy resin and TH-7255 hardener. The YD-535 LV epoxy resin had a viscosity of about 1400 mPa · s and a specific gravity of 1.10–1.20. The TH-7255 hardener had a viscosity of about 60 mPa · s and a specific gravity of 0.98–1.04. This resin-hardener system was chosen due to its low viscosity, good fiber wetting, high bond strength and suitability for VARTM process. These properties allow the resin to be homogeneously saturated, reducing the formation of voids, and permit the production of high-quality composite laminates with improved structural integrity and performance [15].

All laminates were fabricated using the same VARTM process under identical processing conditions to ensure manufacturing consistency. After resin infusion, the laminates were cured at room temperature for 24 h, followed by post-curing at 80°C for 2 h. The fabricated laminates had a nominal thickness of 1.6 ± 0.05 mm, which was verified using a digital micrometer before specimen preparation. Test specimens were machined according to ASTM standards, and their edges were carefully finished to avoid stress concentration. Visual inspection confirmed uniform resin distribution with no significant voids, dry spots, or delamination, ensuring acceptable laminate quality and repeatability of the experimental results. The selected epoxy system is particularly suitable for vacuum-assisted resin transfer molding because its low viscosity facilitates complete impregnation of densely packed fiber fabrics while minimizing void formation. In addition, the cured epoxy provides excellent fiber–matrix adhesion, high interlaminar bonding strength, low curing shrinkage, and good environmental resistance. These characteristics ensure efficient stress transfer from the matrix to the reinforcing fibers, thereby improving both tensile and flexural performance and providing repeatable laminate quality across all specimens.

Selection of Stacking Sequence

The stacking sequence of a hybrid-composite laminate is an important factor that influences its mechanical performance, as the outer layers experience the maximum tensile and compressive stresses under loading. Thus, the proper placement of the reinforcing fibers can have a major effect on the tensile strength, flexural strength, stiffness and the failure behavior of the composite [16–19]. The carbon fiber was chosen to be the main reinforcement because of its high strength, stiffness and load carrying capability. A six-ply carbon fiber core was retained in all hybrid laminate configurations to maintain a consistent structural core and allow for comparative analysis. The stacking details are provided in Figure 1.

Sample	Front side	Rear side
$[0_1/45_1/90_1/-45_1]_8$		
$[0_1^K/0_6^C/0_1^K]$		
$[0_1^G/0_6^C/0_1^G]$		
$[0_1^K/0_6^C/0_1^G]$		
$[0_1^G/0_6^C/0_1^K]$		

Figure 1. Staking sequence of fiber layers.

Five different laminate configurations were designed to study the outer layer reinforcement effect on the tensile and flexural behavior of carbon-rich hybrid composites. Each laminate consisted of eight plies with a thickness of about 0.2 mm per ply. The central six plies were carbon fiber reinforcement while the outer top and bottom plies were varied with Kevlar and glass fibers. Kevlar fibers were chosen for their excellent toughness, impact resistance, and energy absorption; glass fibers were selected for their good strength, dimensional stability, and low cost. This arrangement allowed to evaluate the effect of Kevlar and glass fibers on mechanical response of the laminates individually and in combination. The studied stacking sequences were: (i) pure carbon laminate (C8), (ii) Kevlar–Carbon–Kevlar (K/C/K), (iii) Glass–Carbon–Glass (G/C/G), (iv) Kevlar–Carbon–Glass (K/C/G) and (v) Glass–Carbon–Kevlar (G/C/K).

The stacking sequences were intentionally designed so that the carbon plies remained unchanged in all hybrid laminates while only the outer surface layers were modified. This approach minimizes variations in the primary load-bearing section and enables the influence of Kevlar and glass surface reinforcements to be evaluated independently. Since the maximum tensile, compressive, and bending stresses occur near the laminate surfaces, changing only the outer plies provides a systematic method for studying stress redistribution, crack initiation, interfacial load transfer, and flexural stiffness without introducing additional variables associated with changes in the carbon core [20–22]. The laminate architecture is shown in Figure 2.

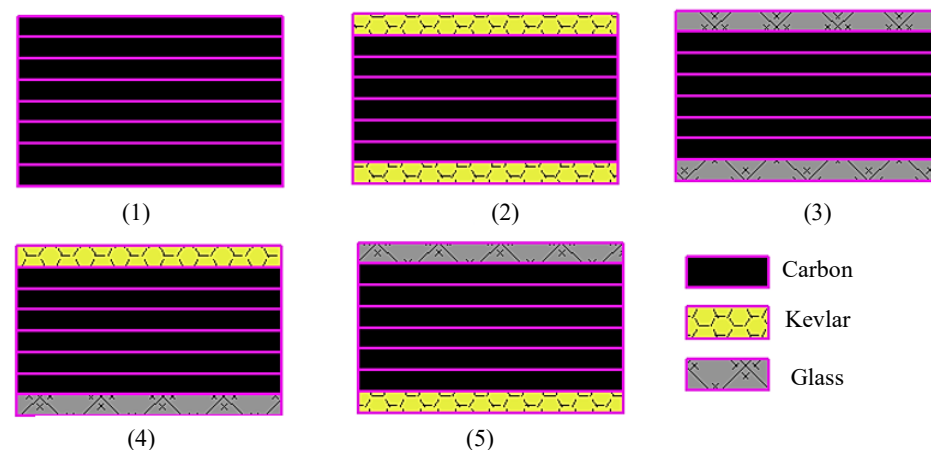
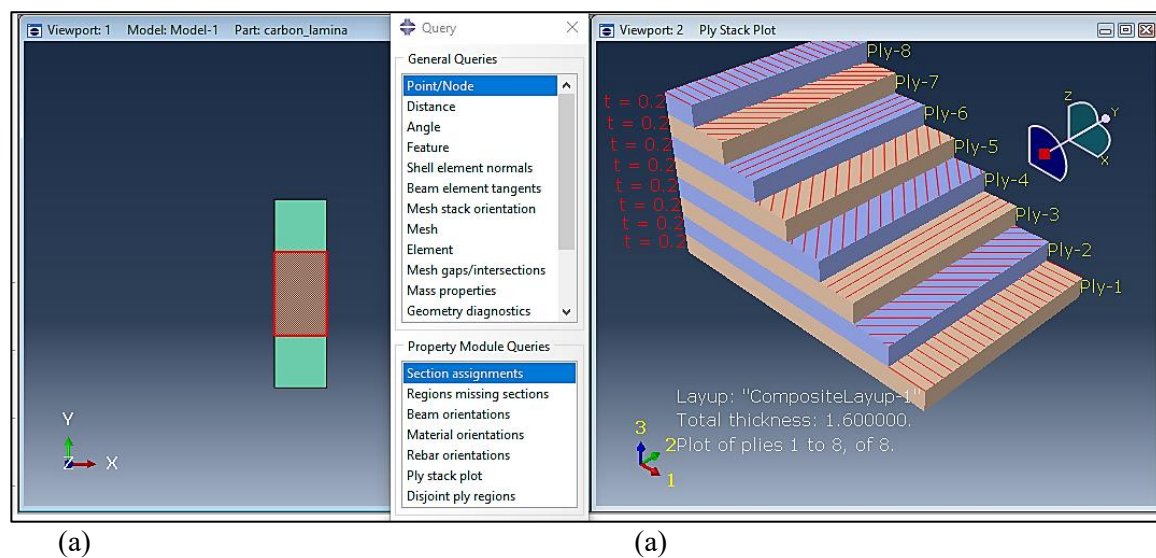


Figure 2. (a): Composite laminate layup in Abaqus and (b): Stacking sequence of a manufactured hybrid composite.

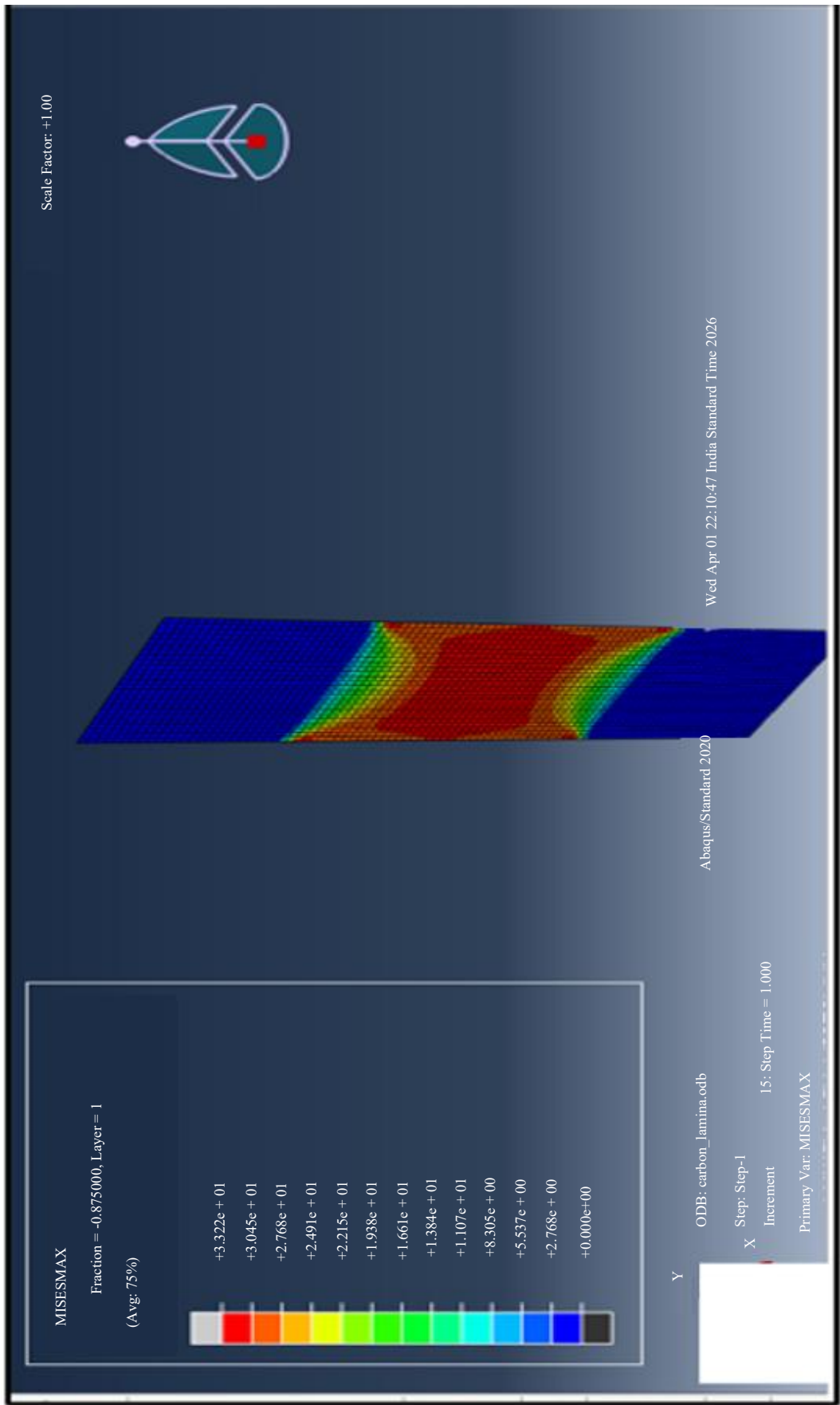
Mechanical Testing and Numerical Validation

Specimens for tensile and flexural testing were prepared in accordance with ASTM standards to evaluate the mechanical performance of the fabricated hybrid-composite laminates. Tensile test specimens were fabricated according to ASTM D3039 with dimensions of 90 mm × 25 mm, while flexural test specimens were prepared following ASTM D7264 with dimensions of 70 mm × 20 mm. The experimentally determined mechanical properties were subsequently utilized for finite element modelling and numerical validation.

Figure 3 shows the setup of tensile testing and Figure 4 represents the flexural test setup. Uniaxial tensile testing was conducted to determine the tensile strength, elastic modulus, and failure behavior of the laminates. The tensile response provides valuable insight into the load-transfer capability between the reinforcing fibers and the epoxy matrix, as well as the effectiveness of fiber hybridization in enhancing mechanical performance. In hybrid laminates, the overall tensile behavior is influenced by the combined contribution of high-stiffness carbon fibers, tough Kevlar fibers, and mechanically robust glass fibers. The flexural performance of the laminates was evaluated using a three-point bending test in accordance with ASTM D7264. The test was used to determine the flexural strength, flexural modulus, and failure characteristics under combined tensile and compressive loading conditions. Since the outer layers experience maximum stresses during bending, the flexural response is strongly affected by the stacking sequence and fiber arrangement within the laminate. The tensile and flexural properties of the manufactured laminates were validated by finite element analysis in Abaqus after the experimental study. The resulting experimental material parameters were used as orthotropic material parameters. The boundary and loading conditions were correctly reproduced for the experimental conditions. The developed models were validated by comparing the numerical predictions with the corresponding experimental results. The experimental setups and the finite element models of tensile and flexural analyses are shown in Figures 3 and 4, respectively.



(a)



(b) **Figure 3.** (a): Experimental setup showing tensile test and (b): Numerical modelling showing tensile test.

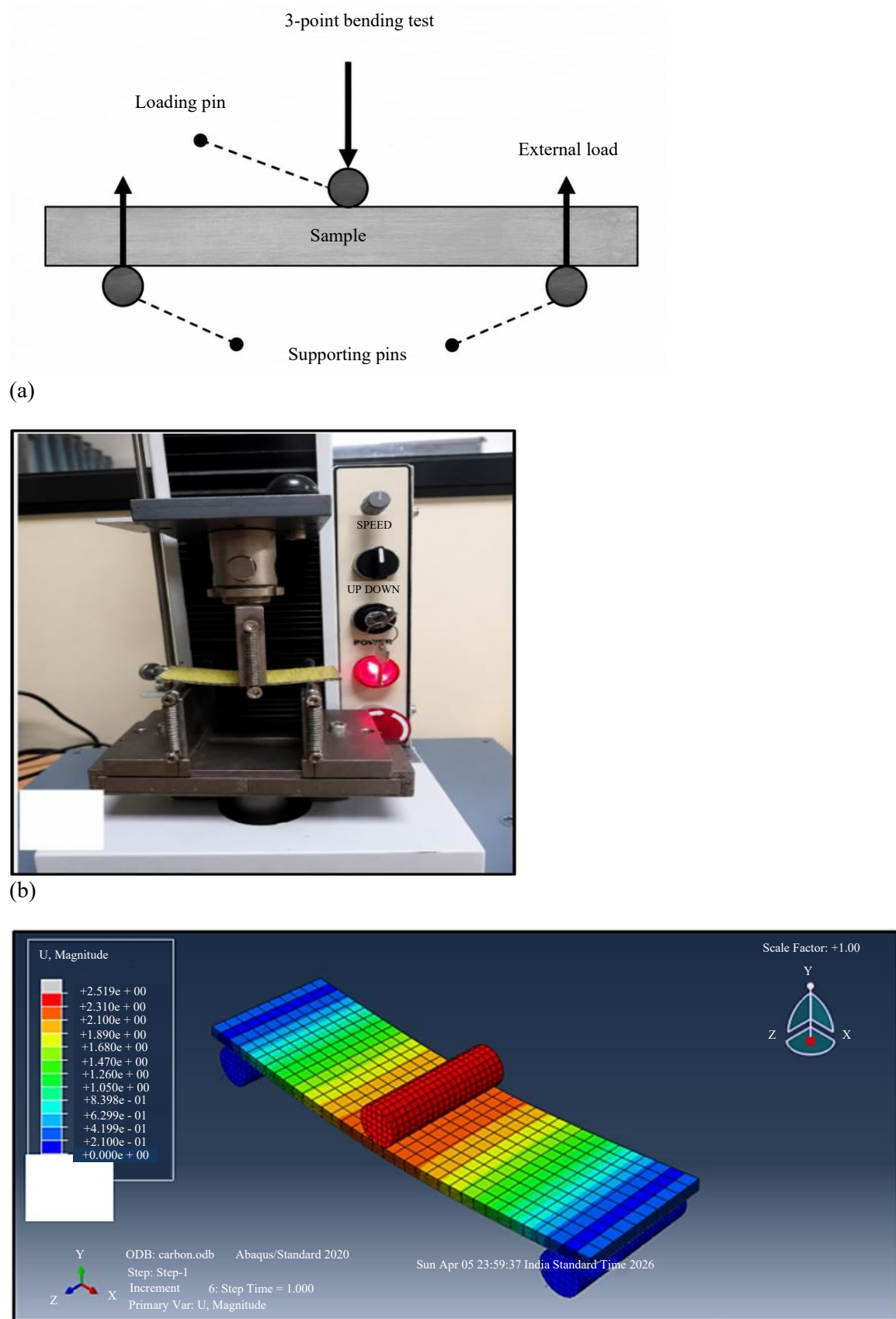


Figure 4. (a): Schematic representation flexural test, (b): Experimental setup showing Flexural test, and (c): Numerical modelling showing Flexural test.

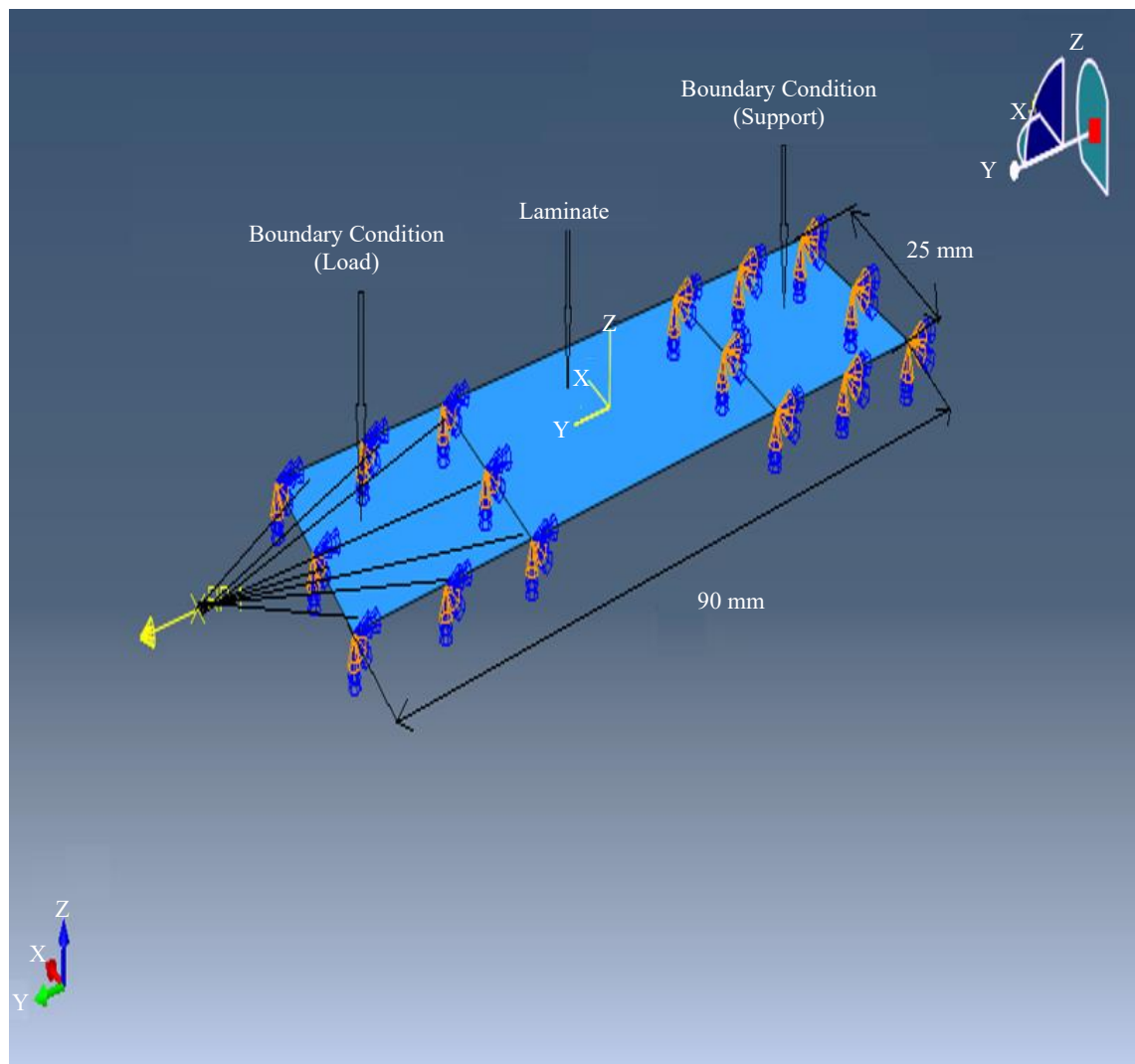
FINITE ELEMENT MODELLING OF TENSILE AND FLEXURAL TEST

The tensile and flexural behaviors of the fabricated hybrid-composite laminates were predicted, and the experimental results were verified using finite element (FE) models in Abaqus/Explicit. Numerical models were constructed to simulate the actual experimental conditions such as specimen geometry, material properties, boundary conditions, and loading configurations.

FE Model of Composite Laminate and Boundary Conditions

Figure 5(a) and (b) depicts the finite element models and the boundary conditions to be used in the numerical simulation of the tensile and flexural behavior, respectively. The tensile and flexural specimens were of dimensions 90 mm x 25 mm x 1.6 mm and 70 mm x 20 mm x 1.6 mm correspondingly following the geometries utilized in the experimental tests. Each laminate consisted of eight orthotropic plies of 0.2 mm thickness for each of the five chosen stacking sequences.

Material parameters obtained from experimental characterization were applied to individual plies to capture the orthotropic response of the composite laminates [23–25]. The boundary and loading parameters were set to simulate the conditions of the ASTM D3039 tensile test and the ASTM D7264 three-point bending test. The created FE models were validated and used for prediction of the stress-strain and load-deflection responses of the laminates. The modeling procedure was validated by comparison of the numerical results with the experimental data.



(a)

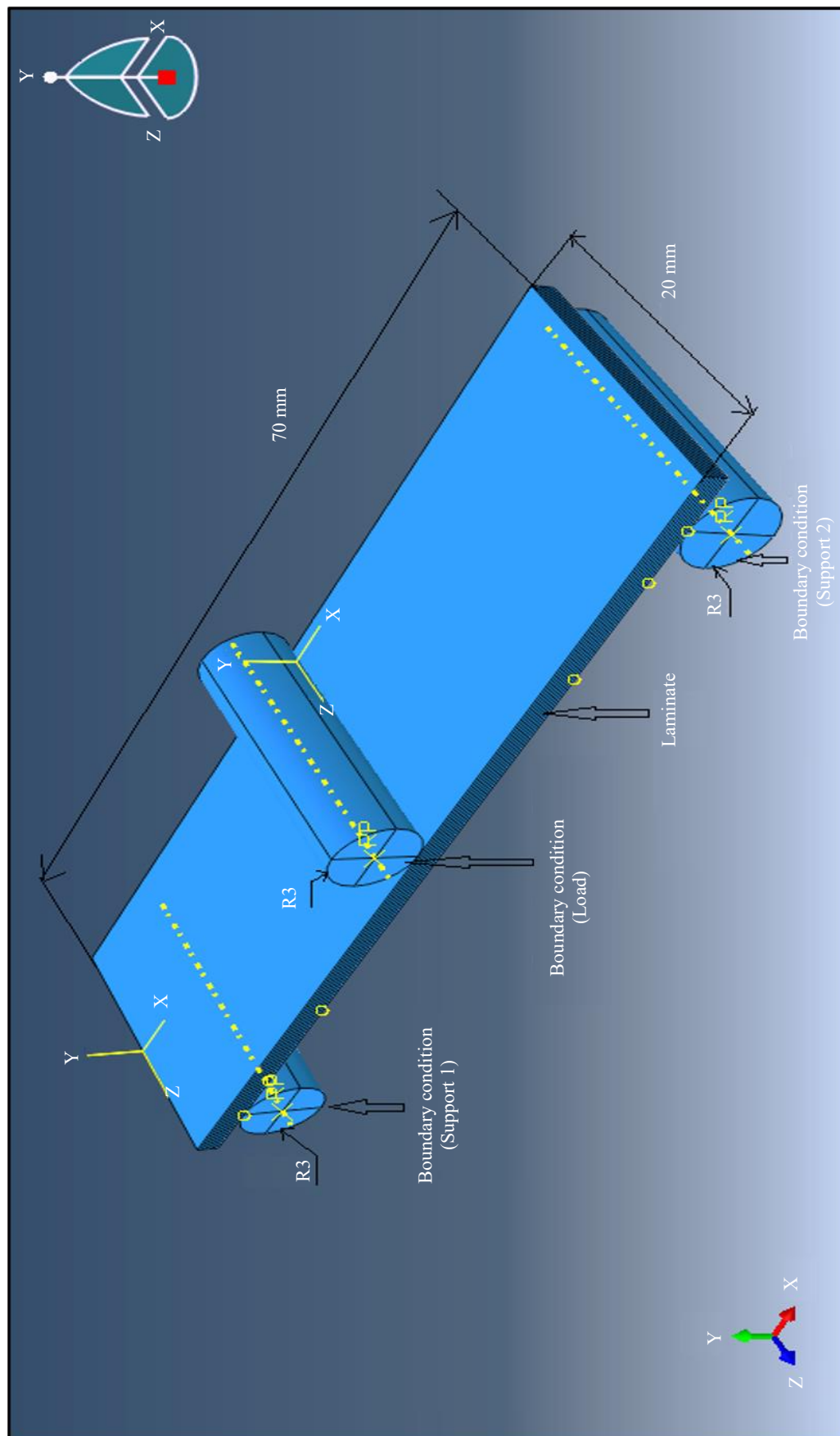


Figure 5. (a): FE model of composite laminate with boundary conditions for tensile and (b): FE model of composite laminate with boundary conditions for flexural.

Meshing of Tensile and Flexural Laminates

The finite element mesh developed for the tensile specimen is shown in Figure 6. The laminate was modelled as an eight-ply composite structure and discretized by means of a structured mesh with a global element size of 1 mm, resulting in a total of 2250 elements. The chosen mesh density was sufficient to properly capture the stress and strain fields, while being computationally efficient (Figure 7). The meshed finite element model for the three-point bending simulation. The model consisted of the composite laminate, loading roller and support rollers and localized mesh refinement was introduced at the contact regions to capture the contact pressures, stress concentration and deformation characteristics accurately. The remaining laminate areas used a relatively coarser mesh for reducing computational costs. The full flexural model was composed of 1230 elements. The anisotropic behavior of the composite laminate was modeled properly by assigning proper global and local coordinate systems to be able to define ply orientations and orthotropic material properties through the laminate thickness correctly [26, 27].

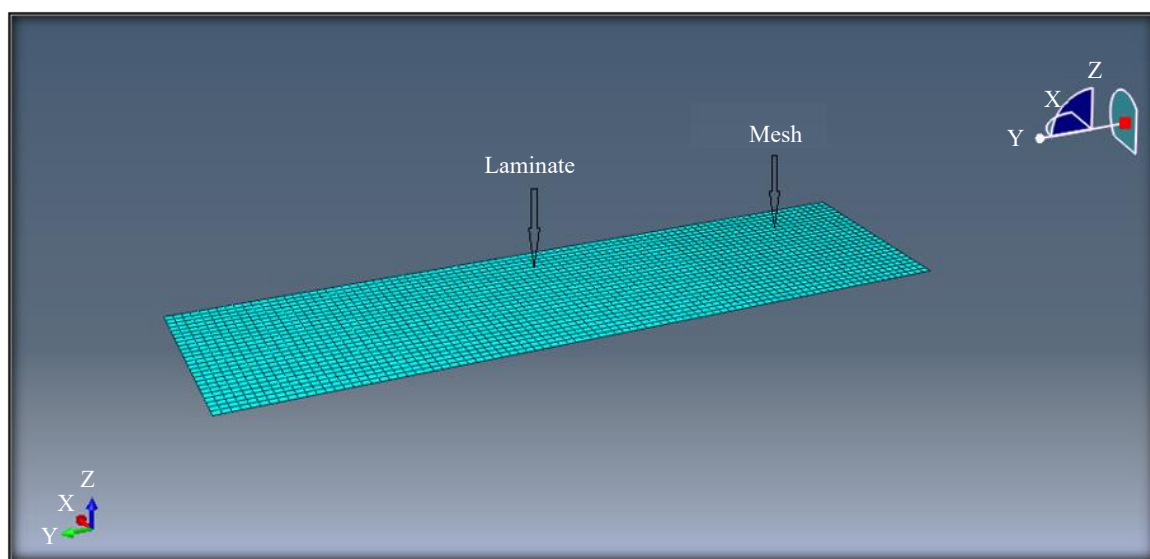


Figure 6. Meshed finite element model of the tensile specimen showing the eight-ply laminate configuration.

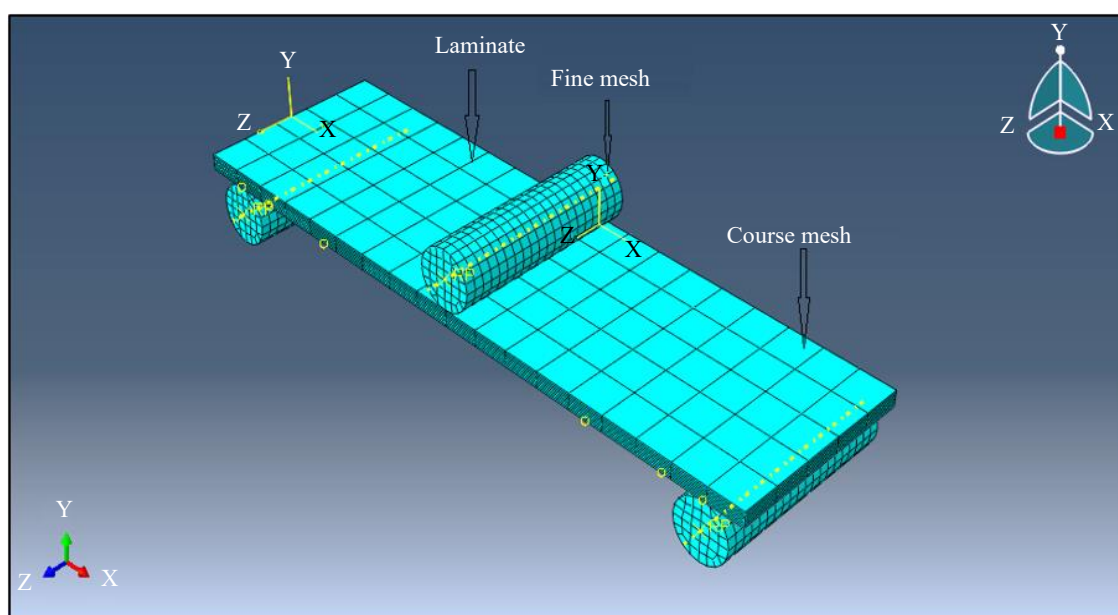


Figure 7. Meshed finite element model of the three-point bending test showing the laminate, loading roller, and support rollers.

Material Properties, Contact Interaction, and Friction

The material properties of the carbon, Kevlar and glass fiber reinforced composite plies – like density, orthotropic elastic constants, strength parameters, and failure characteristics – were obtained from the reported and experimentally validated studies [28–30] and incorporated in the finite element model. The full set of material properties used in the Abaqus simulations are summarized in Table 2. These properties have been extensively used in numerical studies of fiber reinforced composites and have shown good agreement with the corresponding experimental observations.

The interlaminar interactions were modeled adopting cohesive interface properties based on the work of Kaware et al. [4]. This approach allowed a realistic representation of the ply-to-ply bonding behavior. Also, surface-to-surface contact formulations were used to model the interaction of the composite laminate with the loading and support fixtures in the tensile and three-point bending simulations. To account for the variability of frictional behavior due to differences in fiber architecture, orientation and surface morphology, a friction coefficient of 0.30 was assumed based on established literature values. The cohesive and contact properties of the adopted material permitted a realistic representation of the experimental set-up and enabled a reliable prediction of the mechanical response of the composite laminates.

Table 2. Mechanical and physical properties of different composite materials [4].

Property	Carbon	Kevlar	E-glass
Density (kg/m ³)	1600	1650	1790
Longitudinal modulus E_{11} (GPa)	130	17.989	28.87
Transverse in-plane modulus E_{22} (GPa)	7.7	17.989	3.51
Transverse out-of-plane modulus E_{33} (GPa)	7.7	1.948	3.51
In-plane shear modulus G_{12} (GPa)	3.8	1.857	2.98
Out-of-plane shear modulus G_{23} (GPa)	4.8	1.857	2.98
Out-of-plane shear modulus G_{13} (GPa)	4.8	1.857	2.98
Major in-plane Poisson's ratio ν_{12}	0.33	0.08	0.21
Out-of-plane Poisson's ratio ν_{23}	0.33	0.08	0.21
Out-of-plane Poisson's ratio ν_{13}	0.35	0.08	0.21
Longitudinal tensile strength X^T (MPa)	2080	1850	301.198
Longitudinal compressive strength X^C (MPa)	1250	1850	310.785
Transverse tensile strength Y^T (MPa)	60	1850	29.78
Transverse compressive strength Y^C (MPa)	110	1850	31.97
In-plane shear strength S^T (MPa)	290	543	33
Transverse shear strength S^C (MPa)	290	543	33

RESULTS AND DISCUSSION

Comparative Tensile Strength Analysis

FE analysis was used to experimentally test and numerically analyze the tensile behavior of five laminate configurations, $[0_1/45_1/90_1/-45_1]_s$, $[0_1^K/0_6^C/0_1^K]$, $[0_1^G/0_6^C/0_1^G]$, $[0_1^K/0_6^C/0_1^G]$, and $[0_1^G/0_6^C/0_1^K]$, and the specimen sizes are given in Table 3. Figure 8 shows the tensile stress–strain behaviors of all the laminates, and the effect of stacking sequence and outer-layer reinforcement on the tensile performance is highlighted.

Table 3. Tensile strength results.

Samples	Length <i>mm</i>	Width <i>mm</i>	Thickness <i>mm</i>	Experimental analysis		Numerical analysis	
				Tensile strength MPa	Strain %	Tensile strength MPa	Strain %
$[0_1/45_1/90_1/-45_1]_s$	90	25	1.6	185	7.46	180	7.12
$[0_1^K/0_6^C/0_1^K]$	90	25	1.6	210	8.14	203	7.9
$[0_1^G/0_6^C/0_1^G]$	90	25	1.6	245	8.5	236	8.3
$[0_1^K/0_6^C/0_1^G]$	90	25	1.6	356	7.46	339	7.1
$[0_1^G/0_6^C/0_1^K]$	90	25	1.6	315	9.58	289	9.1

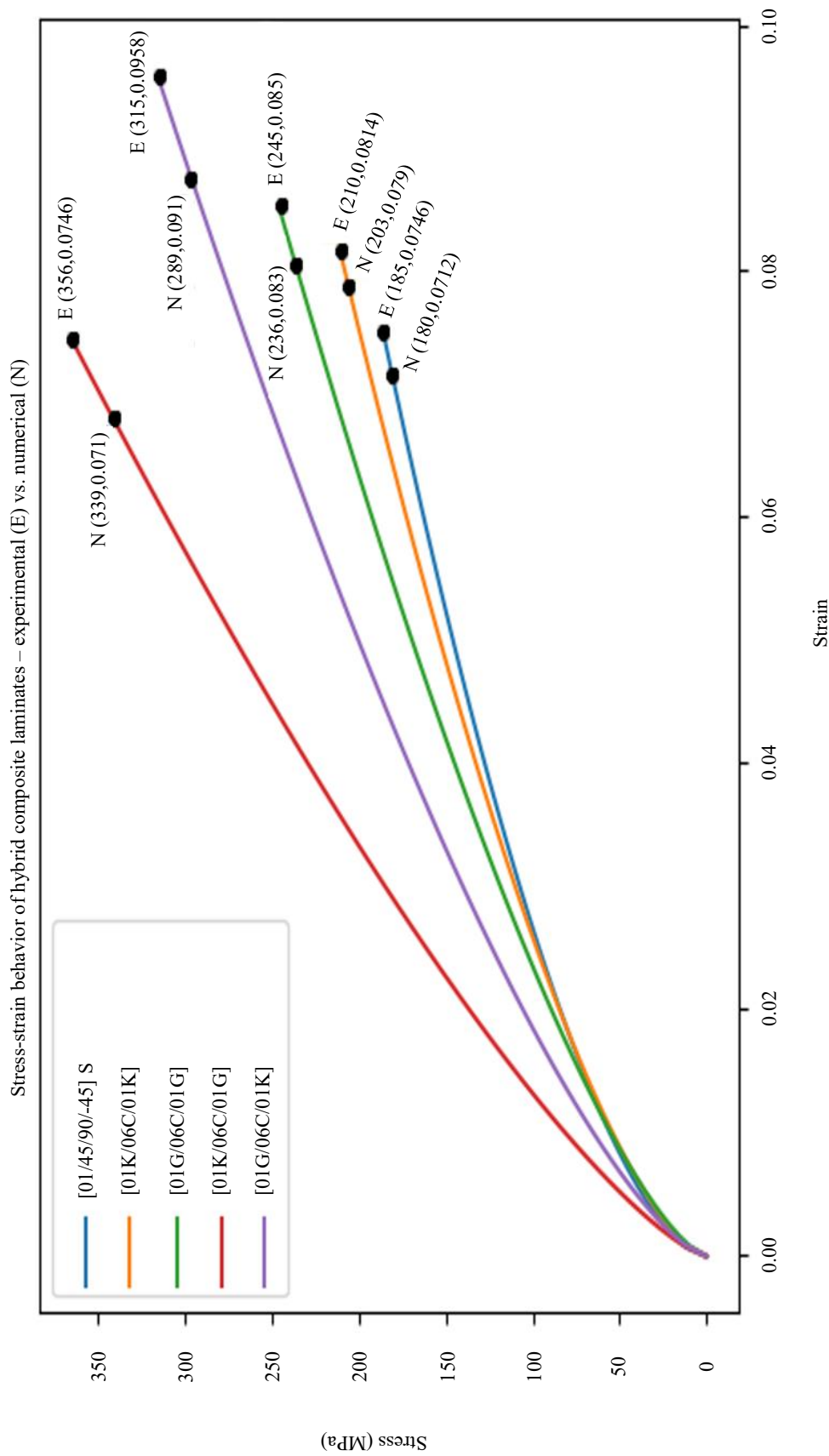


Figure 8. Tensile stress-strain curves of different hybrid composite laminate configurations.

The experimental and numerical stress–strain responses of the studied composite laminates are presented in Figure 9. In general, the numerical predictions are in good agreement with the experimental results with the deviations varying from about 2.7% to 8.3%, which confirms the reliability of the developed finite element model. The stacking sequence plays a key role in the load transfer mechanism, stress distribution and failure propagation within the laminate, thereby having a profound impact on the mechanical behavior of the observed laminate.

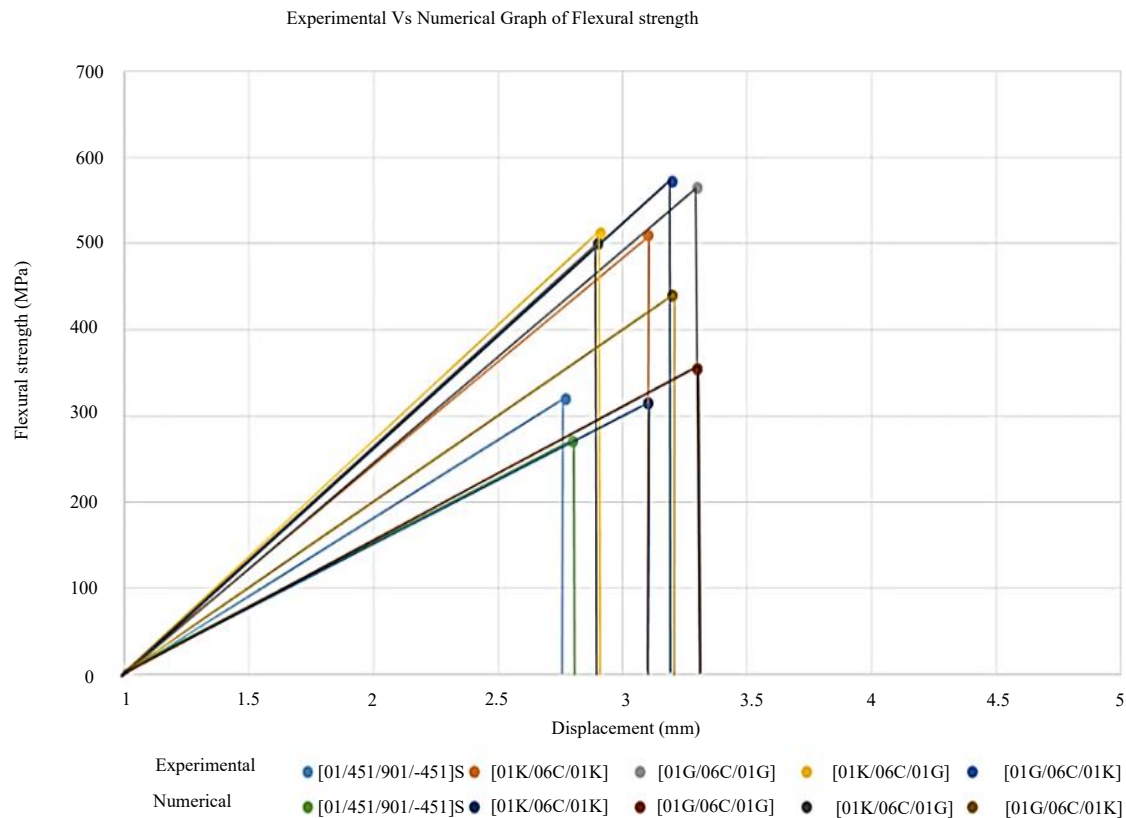


Figure 9. Comparison of experimental and numerical flexural stress–strain curves for different hybrid-composite laminate configurations.

The lowest value of tensile strength was observed for the quasi-isotropic laminate $[0_1/45_1/90_1/-45_1]_s$, with 185 MPa (experimental) and 180 MPa (numerical). This is because of the presence of 90° and $\pm 45^\circ$ plies which are not as effective in carrying axial tensile loads as 0° plies. Under tensile load, much of the load is carried through matrix-dominated deformation and interlaminar shear, giving lower stiffness and strength. The stacking sequence provides balanced in-plane properties, but the lower percentage of load bearing 0° fibers limits the tensile performance. Experimentally, the laminate $[0_1^K/0_6^C/0_1^K]$ shows a higher tensile strength of 210 MPa and with a numerical value of 203 MPa. In this layout, the dominant load carrying plies are six carbon fiber plies in the center because of their high modulus and strength, and the outer plies are Kevlar to provide toughness and crack arresting capability. The external Kevlar layers, however, deform more, due to the lower modulus of Kevlar compared to carbon and glass fibers. This causes a reduction in the overall stiffness of the laminate compared to the glass hybrids. Further increase in tensile strength was observed for the $[0_1^G/0_6^C/0_1^G]$ laminate, with experimental and numerical results showing 245 MPa and 236 MPa, respectively. The glass fibers have higher elastic modulus and better dimensional stability, which will improve the stiffness of the laminate. The Kevlar outer layers were replaced by glass fiber plies. The symmetric arrangement of the glass–carbon–glass layers allows more uniform stress distribution over the laminate thickness and enhances the load transfer from the matrix to the carbon core, thus leading to higher strength and less deformation.

The $[0_1^K/0_6^C/0_1^G]$ laminate showed the highest tensile strength among all the configurations, experimentally 356 MPa and numerically 339 MPa. The performance improvement is due to the hybrid stacking sequence, where the Kevlar and glass fibers are on opposite outer surfaces surrounding a carbon-rich core. The carbon plies carry most of the tensile load efficiently, the glass layer adds stiffness, and the Kevlar layer improves toughness and crack propagation resistance. The asymmetric arrangement serves to effectively redistribute stress and delay the onset of damage, thereby leading to the highest load bearing capacity. In addition, the high-modulus glass layer and the energy absorbing Kevlar layer work together to improve the tensile strength while maintaining the structural integrity. The second strongest configuration experimentally was $[0_1^G/0_6^C/0_1^K]$ laminate with 315 MPa and numerically 289 MPa. However, it showed the highest strain-to-failure (0.0958 experimentally and 0.091 numerically) indicating better ductility and energy absorption capability. The stress distribution through the laminate thickness is changed by altering the order of the Kevlar and glass outer plies. The outer layer of Kevlar has a larger deformation due to its higher elongation at break. Therefore, the laminate can withstand a higher strain before failure. The ultimate strength of this stacking sequence is slightly lower than that of the $[0_1^K/0_6^C/0_1^G]$ lay-up, but the damage tolerance and toughness are greatly improved. This indicates that the positioning of the Kevlar on the outer surface is more beneficial for ductility than for maximum strength.

Overall, the results clearly show that the stacking sequence plays a critical role in determining the tensile response of hybrid-composite laminates. Laminates with higher content of 0° carbon plies show better load carrying capability. The positioning of glass and Kevlar layers plays an important role in stiffness, toughness and failure strain. The $[0_1^K/0_6^C/0_1^G]$ stacking sequence is the best compromise between stiffness and strength, and it shows the highest tensile performance, while the $[0_1^G/0_6^C/0_1^K]$ sequence shows higher ductility and energy absorption. The good agreement between experimental and numerical results also validates the finite element model to describe the effect of stacking sequence on mechanical behavior of hybrid-composite laminates.

Comparative Flexural Strength Analysis

The flexural behavior of five laminate configurations namely $[0_1/45_1/90_1/-45_1]_s$, $[0_1^K/0_6^C/0_1^K]$, $[0_1^G/0_6^C/0_1^G]$, $[0_1^K/0_6^C/0_1^G]$, and $[0_1^G/0_6^C/0_1^K]$ were experimentally evaluated and validated by finite element analysis. The dimensions of the specimens and the experimental and numerical flexural strength values are summarized in Table 4. The flexural stress–strain responses of all laminate configurations are shown in Figure 9, which shows the effect of stacking sequence and outer-layer reinforcement on the flexural behavior of the hybrid composites.

Table 4. Dimensions of flexural test specimens and comparison of experimental and numerical flexural strength values for different hybrid-composite laminate configurations.

Samples	Length <i>mm</i>	Width <i>mm</i>	Thickness <i>mm</i>	Experimental analysis		Numerical analysis	
				Flexural strength MPa	Displacement	Flexural strength MPa	Displacement
$[0_1/45_1/90_1/-45_1]_s$	70	20	1.6	270	2.8	320	2.77
$[0_1^K/0_6^C/0_1^K]$	70	20	1.6	315	3.1	327	3.2
$[0_1^G/0_6^C/0_1^G]$	70	20	1.6	355	3.3	342	3.27
$[0_1^K/0_6^C/0_1^G]$	70	20	1.6	500	2.9	512	2.91
$[0_1^G/0_6^C/0_1^K]$	70	20	1.6	440	3.2	477	3.15

The flexural strength and displacement predicted numerically are in good agreement with the experimental results, which means that the finite element model developed correctly captures the bending response of the hybrid laminates. The differences in flexural behavior are mainly caused by the stacking sequence which controls the distribution of tensile and compressive stress through the laminate

thickness and has a significant effect on the stiffness, the load carrying capacity and the deformation characteristics.

The quasi-isotropic laminate $[0_1/45_1/90_1/-45_1]_s$ had the minimum flexural strength of 270 MPa experimentally and 320 MPa numerically and the displacement of 2.8 mm experimentally and 2.77 mm numerically. The relatively poor flexural performance is due to the existence of $\pm 45^\circ$ and 90° plies, which are not as effective as resist bending loads. In three point bending the maximum tensile and compressive stress occurs in the outer layers and the off-axis plies contribute mainly through matrix dominated shear deformation, rather than direct load carrying. Hence, lower stiffness and strength is obtained compared to the hybrid laminates with mainly 0° fiber orientations.

The flexural strength obtained experimentally and numerically for the $[0_1^K/0_6^C/0_1^K]$ laminate was 315 MPa and 327 MPa, respectively, with the corresponding displacements of 3.1 mm and 3.2 mm. The carbon-rich core efficiently absorbs the bending load, while the Kevlar outer layers provide added toughness and resistance to crack propagation. However, the laminate has larger deflection under loading due to the low modulus of Kevlar fibers and the larger displacement compared to the quasi-isotropic laminate. The symmetric arrangement of Kevlar layers enhances the damage tolerance but restricts the overall flexural stiffness. The $[0_1^G/0_6^C/0_1^G]$ $[01G/06C/01G]$ laminate exhibited an extra increase in experimental and numerical flexural strength to 355 MPa and 342 MPa, respectively, with displacements of 3.3 mm and 3.27 mm, respectively. Glass fibers are stiffer than Kevlar, which allows for more efficient stress transfer, as well as resistance to bending deformation. The symmetric glass–carbon–glass stacking sequence allows the outer glass layers to effectively counteract the maximum tensile and compressive stresses induced during bending, thus increasing the flexural strength and maintaining good structural stability.

The $[0_1^K/0_6^C/0_1^G]$ laminate showed the highest flexural strength compared to all the studied laminates with an experimental value of 500 MPa and a numerical value of 512 MPa with a relatively low displacement of 2.9 mm and 2.91 mm experimentally and numerically, respectively. The improved performance is due to the synergistic effect of hybrid stacking sequence. The carbon fiber core gives a good load-bearing capability, the glass fiber layer gives high stiffness and compressive strength, and the Kevlar layer provides toughness and crack resistance. The asymmetric arrangement under bending makes for efficient redistribution of stress between tensile and compressive regions, thus delaying initiation of failure and enabling the laminate to carry considerably higher loads. The low displacement also shows higher flexural rigidity compared to the other laminates. The $[0_1^G/0_6^C/0_1^K]$ laminate was experimentally characterized by a flexural strength of 440 MPa and numerically by a flexural strength of 477 MPa with displacements of 3.2 mm and 3.15 mm, respectively. Its strength is lower than that of the $[0_1^K/0_6^C/0_1^G]$ laminate but still significantly higher than the symmetric hybrid combinations. The outer glass and Kevlar layers are reversed, changing the stress distribution through the laminate thickness. The Kevlar outer layer has a greater strain to failure and a lower modulus so it deforms more under bending loads. This results in better energy absorption and damage tolerance, but a slightly lower flexural strength. The result revealed that the ply positioning has a significant effect on the bending performance of hybrid laminates.

In general, the results clearly show that the stacking sequence has a significant effect on flexural behavior. Laminates with strategically placed glass and Kevlar layers around a carbon fiber core show better bending performance than the quasi-isotropic and symmetric hybrid laminates. The $[0_1^K/0_6^C/0_1^G]$ laminate has the best combination of flexural strength and flexural stiffness due to the efficient use of the individual benefits of carbon, glass and Kevlar fibers. But the $[0_1^G/0_6^C/0_1^K]$ laminate has better deformation capability and toughness with a slight decrease in strength. The good agreement between the experimental and numerical results further validates the finite element model and confirms its capability to predict the effect of stacking sequence on the flexural response of hybrid-composite laminates.

CONCLUSIONS

In this study, the tensile and flexural behavior of hybrid–FRP laminates reinforced with carbon, glass, and Kevlar and the validation of the experimental results through finite element analysis using Abaqus were experimentally investigated. From the results obtained the following conclusions can be drawn:

- The stacking sequence and fiber hybridization had a significant impact on the mechanical performance of the investigated laminates, showing the importance of laminate architecture for tensile and flexural behavior.
- Hybrid carbon-rich laminates showed better tensile and flexural properties because of their high stiffness and good ability to transfer load.
- Among all investigated configurations, the $[0_1^K/0_6^C/0_1^G]$ laminate exhibited the highest tensile strength (356 MPa) and flexural strength (500 MPa), indicating the beneficial synergistic effect of carbon, glass, and Kevlar fiber hybridization.
- The $[0_1^G/0_6^C/0_1^K]$ laminate showed the highest strain and displacement at failure which indicates enhanced toughness, ductility and energy absorption properties due to the presence of Kevlar reinforcement.
- The symmetric angle-ply laminate $[0_1/45_1/90_1/-45_1]_s$ showed the lowest tensile and flexural strength consistently because the off-axis plies reduced the load-carrying efficiency under both axial and bending loads.
- By the hybridization of carbon, glass and Kevlar fibers, the mechanical properties could be tailored effectively, obtaining the optimum balance between strength, stiffness and damage tolerance by the proper stacking-sequence design.
- The finite element predictions were in good agreement with the experimental results for all the laminate configurations, confirming the accuracy and reliability of the developed numerical models for the prediction of tensile and flexural responses.
- The validated numerical model successfully captured the effect of stacking sequence on the mechanical behavior of hybrid laminates and can be used as a reliable tool for structural performance assessment.

Future Scope

The validated finite element framework developed in this study will offer a reliable platform for future parametric investigations of hybrid-composite laminates. The numerical model can be used in future works to evaluate the influence of the ply orientation, stacking sequence, laminate thickness, fiber volume fraction and hybridization schemes on the tensile and flexural properties. The developed modelling approach can also be extended to study impact resistance, fatigue behavior, progressive damage evolution, thermal stability and failure mechanisms of advanced composite structures. These numerical studies can significantly reduce the time, cost, and experimental efforts required for the design and optimization of advanced lightweight composite materials for aerospace, automotive and structural engineering applications.

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