International Journal of Interdisciplinary Innovative Research & Development (IJIIRD)
ISSN: 2456-236X
Vol. 11 Special Issue 02 | 2026

Finite Element Investigation of the Tensile and Flexural Behaviour of Carbon-Core Hybrid FRP Laminates

[1]Gopal Wadnere, [2]Kiran Kaware
[1] *SOET, Sandip University, Nashik*
[2] *Adsul's Technical Campus, Ahilyanagar*

DOI:10.5281/zenodo.23672047

ABSTRACT

Finite element analysis (FEA) has become an effective tool to predict the mechanical behavior of fiber-reinforced polymer (FRP) composites, thus reducing the need for extensive experimental investigations at the design stage . This paper presents a numerical study of tensile and flexural behavior for carbon-core hybrid FRP laminates using the finite element software, Abaqus. Five laminate configurations were considered. These include a unidirectional carbon fiber laminate and four hybrid stacking sequences, 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). The numerical models were developed by defining orthotropic material properties, laminate layup, boundary conditions, mesh discretization and proper loading conditions based on ASTM standards. The stress distribution, deformation characteristics, and load-displacement response were studied under tensile and three-point bending loading through simulations. Numerical results demonstrate that the carbon-core hybrid laminates have higher stiffness and strength, and the Kevlar and glass fiber outer layers influence the stress transfer and deformation behaviors. The mechanical response and structural performance of the laminates was highly dependent on the hybrid stacking sequence among the configurations studied. The FE models developed form an efficient computational framework for the analysis of hybrid composite structures and can be applied for design and optimization of lightweight engineering components in aerospace, automotive and structural applications.

Keywords: Hybrid FRP Composites, Finite Element Analysis, Abaqus, Tensile Analysis, Flexural Analysis, Laminate Stacking Sequence, Numerical Simulation.

1. INTRODUCTION

Fiber reinforced polymer (FRP) composites are extensively utilized in aerospace, automotive, marine and structural applications because of their high specific strength, stiffness, corrosion resistance and light weight properties[1]. Among the most used reinforcements are carbon, glass and Kevlar fibers, which have complementary mechanical properties. Carbon fibers offer high stiffness and strength, glass fibers give good mechanical performance at a low cost and Kevlar fibers enhance toughness and impact resistance. The hybridization of these fiber can result in composite laminates with improved mechanical performance than single fiber composites[2].

The mechanical behavior of hybrid laminates is greatly affected by fiber orientation, stacking sequence and laminate architecture[3]. Proper design of stacking sequence improves the stress transfer, stiffness and damage tolerance and optimizes the load-carrying capability of composite structures [4], [5]. Experimental testing is the most common method for the assessment of composite laminates but it can be very costly and time-consuming. Therefore, finite element analysis (FEA) has been an effective tool to predict the mechanical response of composite structures during the design stage. Numerical simulations can offer detailed information of stress distribution, deformation and stiffness, and greatly reduce the development time and experimental cost[6].

Abaqus is a commercial software which has been successfully applied for simulation of tensile and flexural behavior of laminated composites. The ability of finite element models to predict the mechanical response of hybrid laminates and to evaluate the effect of various stacking sequences on the structural performance has been demonstrated in previous studies [7]. However, there are only few comparative numerical studies of carbon-core hybrid laminates reinforced by Kevlar and glass fibers.

Hence, the present study is aimed at finite element analysis of tensile and flexural behavior of carbon-core hybrid FRP laminates using Abaqus. Five laminate configurations [0/45/90/−45]s, K/C/K, G/C/G, K/C/G and G/C/K were studied under tensile and three-point bending loading conditions. The stress distribution, deformation and load carrying behavior are investigated by developing numerical models which take into account orthotropic material properties, laminate lay-up and ASTM based boundary conditions. The study proposes an efficient computational framework for optimization of hybrid composite laminates for lightweight engineering applications.

2. MATERIALS AND METHODOLOGY

2.1 Selection of Materials

Carbon T300, Kevlar and woven E-glass fibers were selected for numerical study because of their complementary mechanical properties. Carbon fiber is used for its high stiffness and strength. Kevlar is used for its toughness and impact resistance. E-glass is used for good strength and cost effectiveness. Material properties for the orthotropic finite element model were obtained from manufacturer data and from published literature [8]. The principal properties are listed in Table 1. Figure 1 shows different stacking sequence.

Table 1: Properties of the Fiber

Property	Carbon T300 Fiber	Kevlar Fiber (Aramid)	Woven E-Glass Fiber
Density (g/cm³)	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

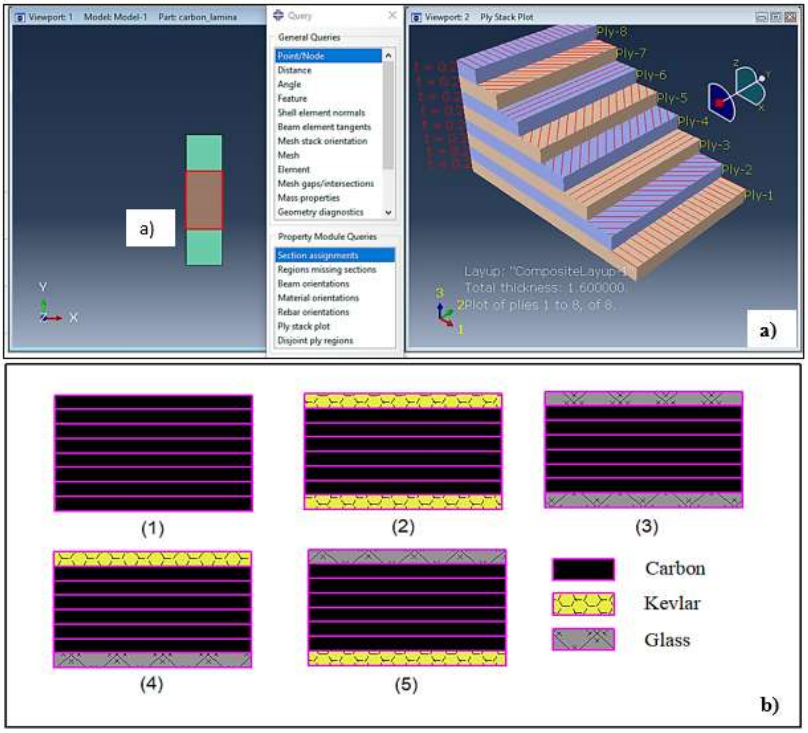


Figure 1 a) Composite laminate layup in Abaqus, b) Stacking sequence of a manufactured hybrid composite

3. FINITE ELEMENT MODELLING OF TENSILE AND FLEXURAL TEST

The tensile and flexural behavior of the hybrid composite laminates were investigated using finite element analyzes with Abaqus/Explicit. Tensile and flexural specimens were made in accordance with ASTM D3039 and ASTM D7264, respectively. The orthotropic material properties obtained from experiments were assigned to each laminate ply and the respective laminate stacking sequences were generated using the Composite Layup module. The boundary conditions and loading configurations were established to simulate uniaxial tensile and three-point bending loading conditions. Numerical models predicted stress distribution, deformation and load-displacement response for different laminate configurations. The finite element models used for the analyzes of tension and bending are presented in Figures 2 and 3, respectively.

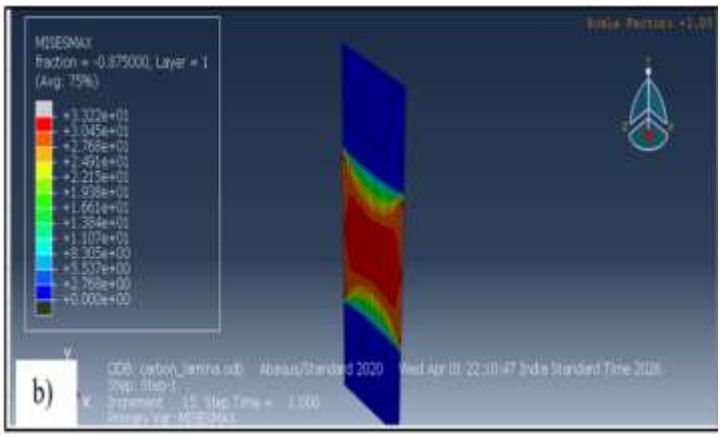


Figure 2 Numerical modelling showing tensile test

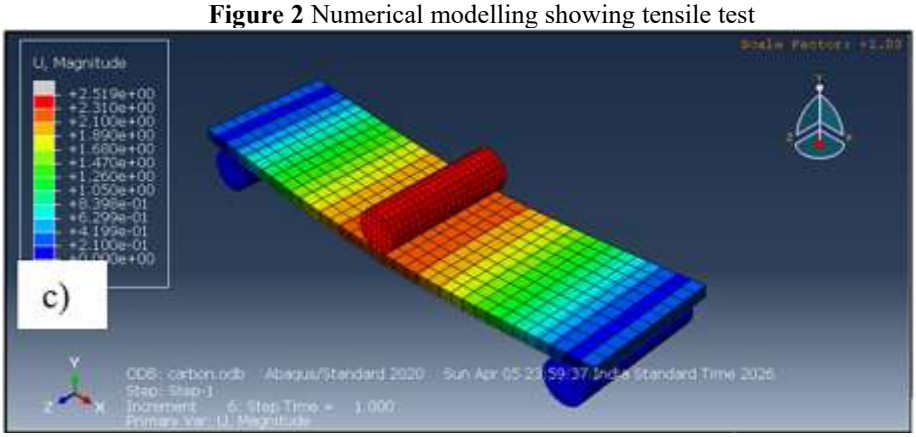


Figure 3 Numerical modelling showing Flexural test.

3.1 FE Model of Composite Laminate and Boundary Conditions

Figures 4 and 5 depict the finite element models and the boundary conditions to be used in the numerical simulation of the tensile and flexural behaviour, 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[9].

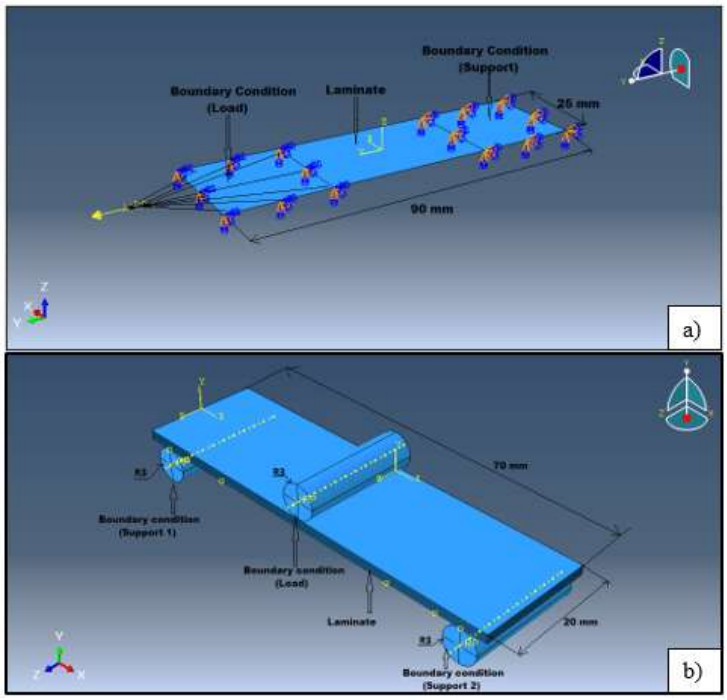


Figure 4. a) FE model of composite laminate with boundary conditions for tensile, b) FE model of composite laminate with boundary conditions for flexural.

Material parameters obtained from experimental characterisation were applied to individual plies to capture the orthotropic response of the composite laminates. 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.

3.2 Meshing of Tensile and Flexural Laminates

The finite element mesh developed for the tensile specimen is shown in Figure 7. 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 6 show 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[1].

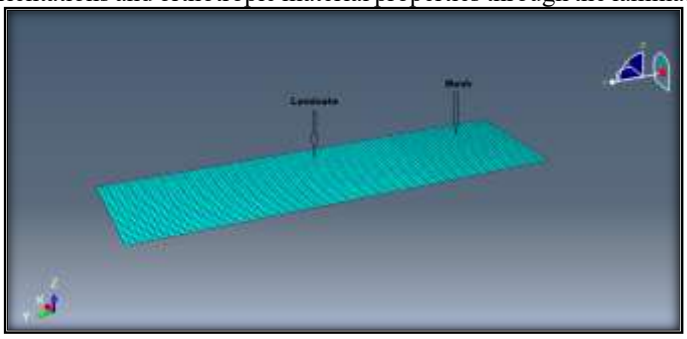


Figure 5. Meshed finite element model of the tensile specimen showing the eight-ply laminate configuration

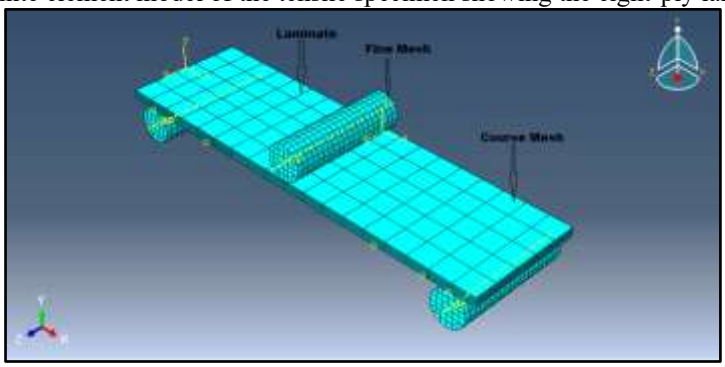


Figure 6. Meshed finite element model of the three-point bending test showing the laminate, loading roller, and support rollers.

3.3 Material Properties, Contact Interaction, and Friction

The orthotropic material properties of the carbon, Kevlar and E-glass fiber composite plies, such as density, elastic constants and strength parameters were obtained from published and experimentally validated studies and were implemented in the Abaqus finite element model. The material properties used in the simulations are shown in Table 2. The interlaminar bonding between successive plies was modeled using cohesive interface properties as discussed in Kaware et al.[10]. The surface-to-surface contact interactions between the laminate, loading indenter and supports were defined with a friction coefficient of 0.30 [11]. With these modeling parameters, the tensile and flexural responses of the hybrid composite laminates were predicted accurately.

Table 2 Mechanical and physical properties of different composite materials [10]

Property	Carbon	Kevlar	E-glass
Density (kg/m³)	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

4. RESULTS AND DISCUSSION

4.1 Tensile Strength Analysis

Finite element (FE) analysis was performed to investigate 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 $[0_1^G/0_6^C/0_1^K]$, The specimen dimensions used in the numerical simulations are listed in Table 3. The stress–strain responses obtained from the simulations are presented in Figure 7, illustrating the influence of laminate stacking sequence and outer-layer reinforcement on the tensile performance of the hybrid composite laminates.

Table 3 Tensile Strength results

Samples	Length	Width	Thickness	Numerical analysis	
				Tensile Strength MPa	Strain %
	mm	mm	mm		
$[0_1/45_1/90_1/-45_1]_s$	90	25	1.6	180	7.12
$[0_1^K/0_6^C/0_1^K]$	90	25	1.6	203	7.9
$[0_1^G/0_6^C/0_1^G]$	90	25	1.6	236	8.3
$[0_1^K/0_6^C/0_1^G]$	90	25	1.6	339	7.1
$[0_1^G/0_6^C/0_1^K]$	90	25	1.6	289	9.1

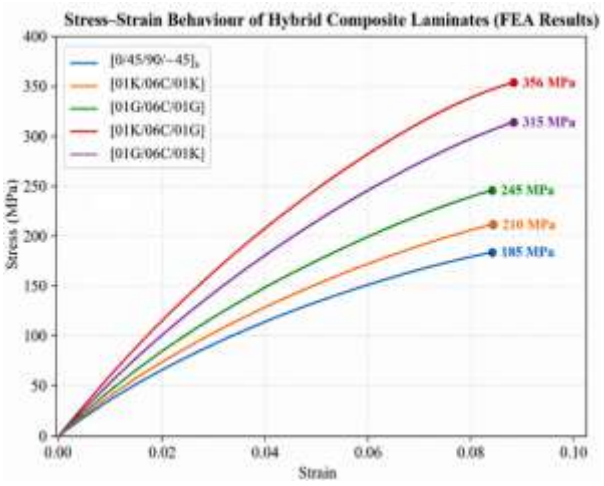


Figure 7 Tensile stress–strain curves of different hybrid composite laminate configurations

The finite element stress–strain responses of the five laminate configurations are presented in Figure 7. The numerical predictions are in good agreement with the experimentally observed trends with deviations less than 10%, confirming the reliability of the developed finite element model. The results indicate that the stacking sequence of the laminate has a strong effect on the tensile behavior by changing the stress transfer mechanism, stiffness and deformation characteristics of the hybrid composite laminates.

Among the studied laminates, the quasi-isotropic $[0_1/45_1/90_1/-45_1]_s$ laminate was found to have the lowest tensile strength (180 MPa) due to the presence of ±45° and 90° plies that are less efficient in carrying axial tensile loads than the 0° plies. The laminate $[0_1^K/0_6^C/0_1^K]$ has tensile strength of 203 MPa. The 6-ply carbon core was able to carry the applied load well, while the outer layers of Kevlar gave the laminate toughness, but decreased the overall laminate stiffness because of lower elastic modulus. Kevlar outer layers by glass fibers $[0_1^G/0_6^C/0_1^G]$ the tensile strength was increased to 236 MPa. This is due to the higher stiffness of the glass fibers and a better transfer of stress between the outer plies and the carbon core.

The maximum tensile strength was found in $[0_1^K/0_6^C/0_1^G]$ laminate (339 MPa) indicating the most efficient load transfer by combining Kevlar and glass fibers in the opposite outer faces. The high stiffness of the glass layer increased the tensile load carrying capacity while the Kevlar layer increased the toughness and crack resistance, thus delaying the damage initiation. The$[0_1^G/0_6^C/0_1^K]$ laminate presented a tensile strength of 289 MPa but the highest strain to failure (0.091), which indicates a better ductility and energy absorption. This is because the outer Kevlar layer had a higher elongation that resulted in more deformation before failure.

Numerical analysis generally supports that the outer-layer reinforcement and stacking sequence are important in the tensile behavior of carbon-core hybrid laminates. The$[0_1^K/0_6^C/0_1^G]$ configuration was the best compromise between stiffness and tensile strength. The ductility and the damage tolerance were higher for the $[0_1^G/0_6^C/0_1^K]$ laminate. The results show that the finite element analysis can predict the mechanical response of hybrid composite laminates and assist in optimizing the laminate architecture for lightweight structural applications..

4.2 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 8, 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	Width	Thickness	Numerical analysis	
				Flexural Strength MPa	**Displacement**
	mm	**mm**	**mm**		
$[0_1/45_1/90_1/-45_1]_s$	70	20	1.6	320	2.77
$[0_1^K/0_6^C/0_1^K]$	70	20	1.6	327	3.2
$[0_1^G/0_6^C/0_1^G]$	70	20	1.6	342	3.27
$[0_1^K/0_6^C/0_1^G]$	70	20	1.6	512	2.91
$[0_1^G/0_6^C/0_1^K]$	70	20	1.6	477	3.15

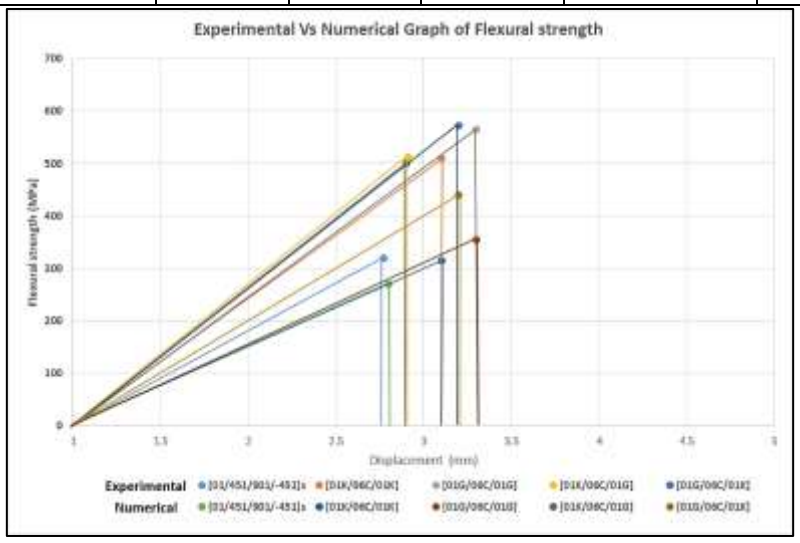


Figure 8 Comparison of experimental and numerical flexural stress–strain curves for different hybrid composite laminate configurations

Figure 8 shows the numerical flexural responses of five laminate configurations. The finite element predictions showed good agreement with the experimental observations and demonstrated the ability of the developed model to accurately capture the bending behavior of the hybrid composite laminates. The results show that the stacking sequence of the laminate is very influential on the flexural strength, stiffness and deformation characteristics of the laminated composite by changing the distribution of the tensile and compressive stresses through the thickness of the laminate.

The quasi-isotropic $[0_1/45_1/90_1/-45_1]_s$ laminate had the lowest flexural strength (320 MPa) among all the laminates studied. This is attributed to the fact that the ±45° and 90° plies are primarily responsible for shear deformation and do not directly contribute to the resistance of bending loads. The $[0_1^K/0_6^C/0_1^K]$ laminate exhibited a flexural strength of 327 MPa, where the load carrying was dominated by the carbon-rich core but the Kevlar outer layers improved toughness but degraded the flexural stiffness due to a lower elastic modulus. The flexural strength was

increased to 342 MPa by replacing the external Kevlar layers by glass fibers [$0_1^G/0_6^C/0_1^G$] which are stiffer than Kevlar fibers and have better resistance to bending deformation.
The highest flexural strength (512 MPa) was observed for the [$0_1^K/0_6^C/0_1^G$] laminate with a displacement of 2.91 mm, which demonstrated a higher bending stiffness and load-carrying capacity. This improvement is attributed to the synergistic effect of the carbon core, the high-stiffness glass outer layer and the tough Kevlar layer, which allow an efficient stress redistribution and a delay of the damage initiation. The [$0_1^G/0_6^C/0_1^K$] laminate had a flexural strength of 477 MPa at a displacement of 3.15 mm and had a better deformation capability and improved energy absorption than the strongest configuration. The outer Kevlar layer has more flexibility, thus it can bear more deformation before failure with a little loss in flexural strength.
The numerical analysis results show that the flexural behavior of hybrid laminates with a carbon core is greatly affected by the stacking sequence and the position of the outer reinforcement layers. The [$0_1^K/0_6^C/0_1^G$] configuration showed the best combination of flexural strength and stiffness, while the [$0_1^G/0_6^C/0_1^K$] laminate showed better ductility and damage tolerance. The results show that the finite element analysis is a useful tool for the optimization of hybrid laminate structures for lightweight structural applications.

5. CONCLUSIONS

Carbon core hybrid FRP laminates with various stacking sequences were used to study their tensile and flexural behavior through finite element analysis in Abaqus. The numerical analysis leads to the following comments:

- The stacking sequence of laminates has a significant effect on the tensile and flexural performance and influences the stress distribution, stiffness and deformation behavior.
- The better mechanical performance was due to the high stiffness and efficient load-transfer ability of the carbon-core hybrid laminates.
- The [01K/06C/01G] laminate showed the highest tensile (339 MPa) and flexural (512 MPa) strength among all the studied configurations, indicating the beneficial synergistic effect of carbon, glass and Kevlar fiber hybridization.
- The [01G/06C/01K] laminate exhibited highest strain-to-failure and flexural displacement, indicating better ductility, toughness and energy absorption.
- The quasi-isotropic [0/45/90/−45] s laminate resulted in the lowest tensile and flexural strengths because of the reduced axial load-carrying capacity of the off-axis plies.
- The numerical results show that an appropriate design of stacking sequences can effectively tailor the mechanical performance of hybrid composite laminates to achieve an optimum balance between strength, stiffness and damage tolerance.
- The developed finite element model is an efficient computational tool for prediction of the mechanical behavior of hybrid laminates and is useful in design and optimization of light weight composite structures.

REFERENCES

[1] L. Alonso, F. Martínez-Hergueta, D. Garcia-Gonzalez, C. Navarro, S. K. García-Castillo, and F. Teixeira-Dias, “A finite element approach to model high-velocity impact on thin woven GFRP plates,” *Int. J. Impact Eng.*, vol. 142, p. 103593, 2020.

[2] K. Kaware and M. Kotambkar, “Low velocity impact response and influence of parameters to improve the damage resistance of composite structures/materials: a critical review,” *International Journal of Crashworthiness*, vol. 27, no. 4, pp. 1232–1256, 2022.

[3] S. Ishtiaq, M. Q. Saleem, R. Naveed, M. Harris, and S. A. Khan, “Glass–Carbon–Kevlar fiber reinforced hybrid polymer composite (HPC): Part (A) mechanical and thermal characterization for high GSM laminates,” *Composites Part C: Open Access*, vol. 14, p. 100468, 2024

[4] K. Kaware and M. Kotambkar, “Hybridization effect of Kevlar and glass fibers on CFRP composite under low velocity impact: Numerical simulations,” *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.*, vol. 237, no. 21, pp. 5122–5133, 2023.

[5] K. Kaware and M. Kotambkar, “Effect of Oblique and Off-Center Impact on CFRP Laminate Under Low Velocity Impact,” *Iranian Journal of Science and Technology - Transactions of Mechanical Engineering*, no. 0123456789, 2024.

[6] H. Wang, J. Guo, and Z. Liu, “Tensile properties and failure of hybrid fiber reinforced polymer composite laminate with different fiber types, hybrid ratios, and stacking sequences,” *Polym. Compos.*, vol. 46, no. 10, pp. 9348–9364, Jul. 2025.

[7] K. Kaware and M. Kotambkar, “Hybridization effect of Kevlar and glass fiber on carbon/epoxy composites to enhance the damage strength under low velocity impact. Part II: Numerical simulations,” *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.*, 2024.

[8] K. Kaware, M. Kotambkar, A. Sontakkey, and N. Talekar, "Finite element analysis of CFRP composite under low velocity impact to improve the impact strength," *International Journal of Crashworthiness*, vol. 28, no. 6, pp. 717–731, 2023.

[9] C. Stephen, S. R. Behara, B. Shivamurthy, R. Selvam, S. Kannan, and M. Abbadi, "Finite element study on the influence of fiber orientation on the high velocity impact behavior of fiber reinforced polymer composites," *International Journal on Interactive Design and Manufacturing*, vol. 16, no. 2, pp. 459–468, 2022.

[10] K. Kaware and M. Kotambkar, "Experimental investigation of hybridization effect of Kevlar and Glass fibers on CFRP composite under low velocity impact," *International Journal of Crashworthiness*, vol. 29, no. 2, pp. 187–197, 2024,

[11] S. Ekşi, F. E. Danyildiz, N. Özsoy, and M. Özsoy, "Tensile, bending, and impact properties of laminated carbon/aramid/glass hybrid fiber composites," vol. 65, no. 12, pp. 1826–1835, 2023, doi: doi:10.1515/mt-2023-0207.