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CLT-Based Mechanical Characterization of Hybrid Composites with Carbon/Kevlar/Steel and Glass/Kevlar/Steel Layers

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Abstract. The composite materials with hybrid structure with use of metalsare gaining attention nowadays. This article presents a step by step method for performing Classical Laminate Theory (CLT) for calculations on hybrid laminates with different stacking sequences. Hybrid fiber metal laminates (FMLs) provide an effective way to maintain stiffness, strength, and damage resistance for advanced structural applications. This study compare two hybrid laminates: Carbon/Kevlar/Mild Steel Wire Mesh (CKMS) and Glass/Kevlar/Mild Steel Wire Mesh (GKMS), byusing Classical Laminate Theory (CLT).Both laminates were physically fabricated using the hand lay-up technique maintaining the same overall thickness and number of layers, primarily to maintain a constant fiber volume fraction of 50%. The mechanical properties reported were theoretically predicted by means of Classical Laminate Theory by evaluating the extensional (A), coupling (B) and bending (D) stiffness matrices. The CKMS laminate showed good stiffness, with tensile moduli of 148.81 &130.81 GPa in X and Y directions respectively compared with 85.70 &72.30 GPa respectively for GKMS. Its flexural modulus reached to92.75 GPa, more than 200% higher that of GKMS **(**30.24 GPa**),** while the shear modulus varied from 25.79 GPa (GKMS) to 40.22 GPa(CKMS) due to the contribution of carbon fibers and ±45° mild steel mesh. The results highlight the strong influence of carbon-based hybridaz tion and stacking sequence on-extensional, bending, and shear responses, while the glass-based system offers a more compliant and cost-effective alternative. The proposed CLT-based comparison framework supports the design of lightweight, high-stiffness components for aerospace panels, UAV structures, automotive skins, marine components, and impact-resistant engineering applications.

Keywords: Hybrid laminates, Classical Laminate Theory, ABD matrix, Fiber orientation, Structural stiffness.

Nomenclature and Glossary

In order to make the discussion transparent to the audience in any field of engineering, the definitions of the following acronyms, symbols and technical terms will be used in this study:

CLT: Classical Laminate Theory-A theoretical model on which the mechanical behavior of thin composite laminates is predicted using an in-plane forces and moments relative to strains and curvatures.

FML: Hybrid fiber–metal laminates

ABD Matrix: The integrated stiffness matrix of a laminate, consisting of the extensional (A), coupling (B), and bending (D) matrices.

GSM: Grams per Square Meter-A standard measure of the areal density or surface weight of fiber reinforcements.

CKMS: Carbon/Kevlar/Mild Steel-The hybrid laminate configuration investigated as Laminate 1.

GKMS: Glass/Kevlar/Mild Steel-The hybrid laminate configuration investigated as Laminate 2.

E_1, E_2: Youngs longitudinal and transverse Moduli of one ply (lamina).

G_{12}: Shear-in plane modulus of a lamina.

$\boldsymbol{v_{12}}$: Ratio of transverse strain to longitudinal strain when axial loaded (major Poisson ratio).

[Q] and [$\bar{Q}$]**:**Simplified and transformed reduced stiffness matrices, which specify the stress strain relation of a single ply in principle and global coordinates.

[A]: Extensional Stiffness Matrix-Relates in-plane forces to mid-plane strains.

[B]: Coupling Stiffness Matrix-Quantifies the interaction between in-plane forces and bending curvatures.

[D]: Bending Stiffness Matrix-Relates bending moments to curvatures, representing out-of-plane rigidity.

Anisotropy: A characteristic of materials where mechanical properties vary depending on the direction of the applied load.

Bending-Extension Coupling: A mechanical phenomenon where axial loading induces bending or twisting in a laminate due to an asymmetric stacking sequence.

Fiber Volume Fraction (v_f): The percentage of the total volume of a composite material occupied by the reinforcing fibers.

Introduction

Hybrid composite materials have been of increasing concern in structural and mechanical engineering practice because of their ability to include several the desired properties, which includes high specific strength, high resistance to corrosion, energy absorption, and adjustable mechanical [1][2][18]. Such systems take advantage of the special characteristics of various reinforcing phases like carbon, glass, Kevlar fibres, metallic wire meshes and polymeric matrices like epoxy to develop materials that have better performance-to-weight ratios and enhanced multi-functionality [4][5]. The combination of the various fibres enables the hybrid laminates to achieve an optimal balance between stiffness, strength, toughness and cost-efficiency as they are specifically applicable to the aerospace, automotive, marine as well as defence sectors [15][7].

The traditional single-fibre composite is limited mostly by inherent change in the material. An example, for carbon fibres, which have high tensile and flexural stiffness but they are brittle in the impact loading [8][9]. On the other hand, Kevlar fibres are tough and have high impact resistance but with low compressive and transverse strength [10][23]. Glass fibres, while moderately strong and economically viable, may fall short in high-performance environments requiring superior fatigue or thermal resistance [28][17] Integrating mild steel wire mesh into these composites further enhances mechanical performance especially in shear and impact resistance by distributing load more effectively and improving inter-laminar stress transfer when embedded in an epoxy [12][13].

The present work extends Classical Lamination Theory beyond its standard textbook application to homogeneous fibre–polymer laminates by introducing a hybrid fibre–metal–mesh architecture that integrates mild steel wire mesh with carbon, glass, and Kevlar plies. Unlike conventional Fibre Metal Laminate (FML) studies that primarily examine aluminium–fibre systems such as GLARE and CARALL with emphasis on impact or fatigue behavior, this study focuses on stiffness and coupling characteristics using the complete ABD formulation[4][9][17][19][39][41][42]. While CLT has been applied to predict the stiffness behavior of conventional fibre-reinforced polymers and established Fibre Metal Laminates (FMLs) such as GLARE with continuous metallic sheets [4][17][39], most existing analytical and experimental investigations focus on traditional metal–fibre architectures. In addition, a large portion of recent FML research concentrates on impact response and damage mechanisms rather than stiffness modeling using CLT [40]. In this, there is a gap in the application of CLT to **hybrid laminates with mild steel wire mesh as a secondary reinforcement**. The strategic placement of wire mesh to enhance inter-laminar shear and impact resistance which modify the bending–extension coupling behavior in ways that are not captured by conventional laminate models. At present, a controlled, CLT-based comparison between a steel-wire-mesh hybrid laminate and a traditional all-fibre laminate of identical ply count, thickness, and fibre volume fraction is lacking. This study addresses this gap by employing CLT to quantify how the integration of mild steel wire mesh influences the complete ABD stiffness matrix particularly the coupling and bending components thereby providing design guidance for next-generation lightweight and damage-tolerant composite structures.

This paper uses CLT to compare and contrast the behaviour of two hybrid epoxy laminates in regard to stiffness behaviour. The two laminates are similar in the number of ply and the thickness, only that the fibre types and stacking structure vary. Through calculation of the overall ABD stiffness matrices, this paper determines the effects of fibre hybridization on the extensional stiffness, the coupling effect and the bending performance. The findings can be used as a theoretical reference in practice, as well as in designing and optimising fibre metal laminates in the contexts where the reduction of weight, impact resistance, and structural reliability are [8][18][12].

1. Materials and Methods

1.1 Materials Used

These hybrid composite laminates were made by employing four varieties of reinforcements in the form of carbon fiber, Kevlar fiber, glass fiber and mild steel mesh wire incorporated in a thermosetting epoxy resin content of the laminate. Fiber reinforcement was done at a surface weight of 300 grams per square meter (GSM), and a constant weight ratio of 50:50 fiber/resin was used to achieve the best impregnation, even distribution of load, and manufacturability of the structure [3]. Unidirectional carbon fibers were used because they have superior tensile strength and stiffness and because they were purposefully placed at 0^0 and 90^0 in the laminate so that they could carry maximum axial and transverse loads. Kevlar fibers which are the best in toughness and resistance to impact were used at 0^0 orientations in order to promote longitudinal tensile behavior and better damage tolerance when progressing under dynamic loading conditions. A single type of $+\text{-}45^0$ orientations was used with mild steel (MS) wire mesh to add ductility and interlayer toughening in addition to better in-plane shear behaviors. The $+\text{-}45^0$ and 90^0 oriented woven glass fibers were used to provide a more economical way of supporting off-axis and transverse loading without excessive effect on mechanical integrity. The type of matrix system was Araldite LY566 and Aradur 22,962 (hardener) [6], which offered environmental inclusivity, dimensional stability, and effective transfer of stress between dissimilar phases of reinforcement during mechanical loading and curing.

Two hybrid laminate systems were manufactured and analytical compared, including: Carbon/Kevlar/Mild Steel wire mesh and Glass/Kevlar/Mild Steel wire mesh laminates. The high stiffness and load-bearing capability of carbon fibers, moderate cost-effectiveness and stiffness of glass fibers, and toughness and damage resistance of Kevlar

fibers were used. M.S. wire mesh was also applied as another reinforcement to enhance the inter-laminar load transfer and shear resistance. All layers were supposed to be parallel in the main direction of the material in accordance to CLT. Both the lamina were treated as orthotropic, linear elastic materials characterized in terms of their elastic constants. An epoxy resin matrix was also assumed to provide sufficient bonding and load compatibility between the fiber layers and the steel mesh.

The laminate stacking patterns were clearly stipulated in the manuscript and they were utilized in the construction of the laminate stiffness matrices. Analytical homogeneity was applied with uniform thickness of the ply and identical fiber volume fraction. In spite of the fact that the study is mainly analytical, the laminates are associated with configurations that may be produced using traditional techniques like hand lay-up, then compression molding or vacuum bagging, and meaningful comparisons can be made between CLT predictions and experimental flexural performance.

1.2 Material Properties

The reinforcement materials are important in ensuring the required degree of mechanical performance. The main reinforcements were carbon fiber, glass fiber and Kevlar fiber because they had different elasticity properties. Carbon fiber is very stiff with longitudinal modulus of 135Gpa(E_1), transverse modulus of 10Gpa(E_2), shear modulus of 5Gpa(G_{12}) and Poisson ratio of 0.28. At the balance point of mechanical behaviour, glass fiber exhibits balanced behaviour $E_1 = 50$ GPa, $E_2 = 15$ GPa, $G_{12} = 5$ GPa, and $\nu_{12} = 0.28$, while Kevlar fiber provides enhanced toughness with $E_1 = 76$GPa, $E_2 = 5$ GPa, $G_{12} = 2$ GPa, and $\nu_{12} = 0.34$. Each of the fibers was woven in mat form with the areal density of 300 GSM. The secondary reinforcement is done with mild steel wire mesh to increase stiffness and load bearing capacity. The material of the mesh was low-carbon mild steel, the wire diameter is 1 mm, and the isotropic elasticity, which comprises the Youngs modulus and shear modulus is 200 Gpa, and Poisson ratio is 0.30 for solid wire

1.3Laminate Configuration

Two hybrid laminates of different stacking sequences were created and tested. The laminates were developed with each laminate having exploited directional strengths of the constituent and still being balanced and symmetric. Tensile strength, flexural strength and shear strength of fiber hybrid composite laminates is quite different in relation to sequencing of fiber stacking [11].

1.4 Laminate Configuration and Design Logic

The stiffness of the hybrid laminates is mainly determined by stacking arrangement, ply orientations, thickness distribution and addition of mild steel wire mesh layer. Both laminates have the same number of ply and a combined thickness so that a fair comparison can be made of CLT based. The combination of 0^0, 90^0, and $+\text{-}45^0$ orientations can achieve effective multi-axial load transfer with 0deg plies controlling the extensional stiffness A_{11}, 90^0 plies controlling the A_{22} and $+\text{-}45^0$ plies controlling the in-plane shear stiffness A_{66}. The $+\text{-}45^0$oriented mild steel wire mesh enhances shear transfer and inters laminar redistribution stress, alters B matrix behavior, reflected on bending-extension coupling. The stiffness and location of outer plies determine the bending stiffness D matrix, where carbon and Kevlar plies close to the surfaces enhance D_{11} and D_{22}. Therefore, the chosen stacking structure has a direct control on the extensional, coupling and bending responses through the ABD formulation.

Laminate 1 (CKMS): Carbon/Kevlar/Mild Steel Wire Mesh

Stacking Sequence: [0° Carbon / 0° Kevlar / +45° MS / −45° MS / −45° MS / +45° MS / 0° Kevlar / 90° Carbon].The stacking sequence is shown in Figure 1.

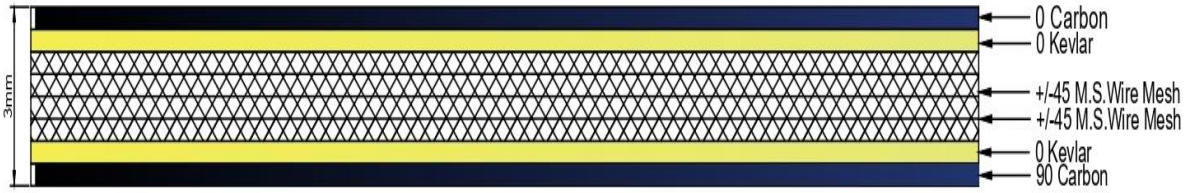

Fig. 1. - Laminate 1- Carbon+Kevlar+M.S.Wire Mesh.

This eight-ply hybrid laminate combines the high stiffness of carbon fiber with the toughness of Kevlar and the ductility of mild steel mesh. The stacking was optimized to enhance tensile performance along the longitudinal axis while preserving transverse and shear strength.

Laminate 2 (GKMS): Glass/Kevlar/Mild Steel Wire Mesh

Stacking Sequence:[+45° Glass / -45° Glass / 0° Kevlar / +45° Mild Steel / -45° Mild Steel / 0° Kevlar / -45° Glass / 90° Glass].The stacking sequence is shown in Figure 2.

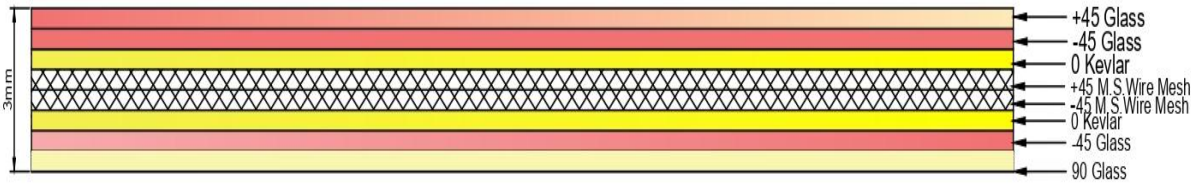

Fig. 2. - Laminate 2 - Glass+Kevlar+M.S.Wire Mesh.

This configuration emphasizes shear and flexural response with fewer layers. The use of woven glass fiber in off-axis and transverse directions helps reduce cost while contributing to a moderate-strength, high-ductility design.

1.5 Fabrication of Hybrid structure Composite Laminates

Overall, composite materials are manufactured with different number of processes. The choice of a specific production method strongly depends on chemical properties of matrix, and also the nature of final product's shape. Hand layup process was selected because it enables precise placement of composite layers and the mild steel wire mesh, ensuring good alignment, uniform resin impregnation and good interfacial bonding.

1.5.1 Setup for laminate manufacturing

After the hand layup process is finished the setup for further process is as shown in Figure 3.

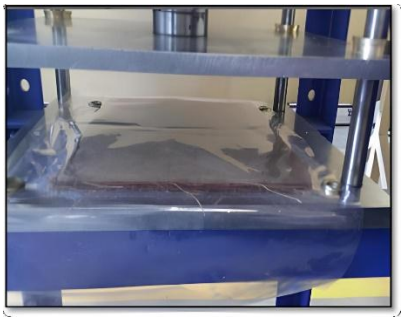

Fig.3.-Setup for laminate manufacturing

1.5.2 Volume fraction Calculation

Fiber volume fraction is the percentage of fiber volume in the entire volume of a fiber-reinforced composite material. The details are listed in Table 1

Table1. Volume fraction calculation

Sr. No	Carbon/Epoxy laminate	Weight of laminates(g)	No. of plies	Weight of fiber(g)	Weight of matrix(g)
1	Laminate1	440	8	250	190
2	Laminate2	440	8	250	190

1.5.3Volume Fraction of Hybrid composite fiber in Hybrid Composite/Epoxy Laminates And (2).

Volume fraction of the Hybrid fibre in the hybrid composite/Epoxylaminatesof440 g, v is given by the following formula.

$$V_{cf} = \frac{(W_{cf}/\rho_{cf})}{(W_m/\rho_{m})+(W_{cf}/\rho_{cf})} x100 \quad (1)$$

$$= \frac{250/1.58}{190/1.22+250/1.58} x100 \quad (1.1)$$

$$= 50.39 \cong 50\%$$

where W_{cf}=Weight of Carbon fibre

ρ_{cf}=Density of Carbon fibre

W_m= Weight of matrix

ρ_m=Density of matrix.

1.6 Manufactured Laminates

The manufactured laminate CKMS is represented in Figure 4 and GKMS is represented in Figure 5 respectively.

Fig.4. - Laminate 1 (Carbon+Kevlar+M.SWire) after manufacturing.

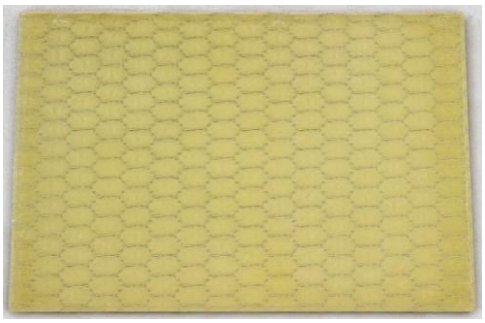

Fig. 5. - Laminate 2 (Glass+Kevlar+M.S. Wire) after manufacturing.

1.7 Simplified Classical Laminate Theory Methodology

The systematic methodology presented in this work consists of a structured sequence involving (i) selection of materials (carbon, glass, Kevlar, and mild steel wire mesh), (ii) stacking sequence design including ±45° mesh layers, (iii) analytical evaluation of laminate stiffness using Classical Lamination Theory (ABD formulation), (iv) fabrication of hybrid laminates via hand lay-up, each step is explicitly defined to ensure repeatability and consistency across laminate configurations.

Moreover, the suggested framework is scalable since the identical CLT-based design analysis validation pipeline can be applied directly to other fiber-metal hybrid laminates by replacing other types of fibers, metal meshes, volume fractions or orientations without changes in the analytical or experimental workflow.

The simplified Classical Laminate Theory methodology, which is shown in figure 6, describes the process starting with the input of material properties through to the development of a stiffness matrix and the effective laminate property assessment.

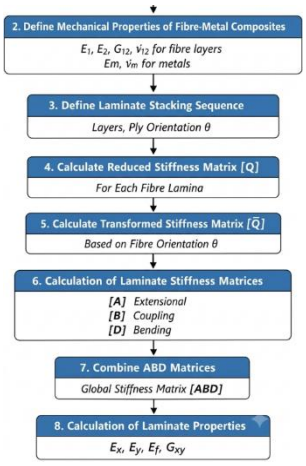

Fig. 6.-Simplified Classical Laminate Theory (CLT) Methodology Flowchart

1.8CLT-Based Theoretical Analysis

Analytical prediction of the mechanical behavior of the hybrid composite laminates under in-plane loading conditions and bending were made by use of Classical Laminate Theory (CLT). CLT assumes linear elastic behavior, ideal bonding between layers, and negligible transverse shear deformation, making it suitable for analyzing thin laminate structures [15]

1.8.1 Reduced Stiffness Matrix [Q]

The constitutive behavior of a single orthotropic lamina in its principal material axes is represented using the reduced stiffness matrix [Q], defined as [26]

$$\begin{bmatrix} \sigma x \\ \sigma y \\ \sigma xy \end{bmatrix} = \begin{bmatrix} Q_{12} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} . \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \quad (2)$$

The components are as follows:

$$Q_{11}=\frac{E_1}{(1-\nu_{12})}\ , Q_{12}=\frac{\nu_{21}E_1}{(1-\nu_{21}.\nu_{21})}\ , Q_{22}=\frac{E_2}{(1-\nu_{12}\nu_{21})}, Q_{66}=G_{12},\ \ \nu_{21}=\nu_{12}.\frac{E_2}{E_1} \quad (3)$$

where $E_1$is Young's modulus in the longitudinal direction.

E_2 is Young's modulus in the transverse direction.

ν_{12} &$\nu_{21}$are poisons ratio

G_{12}= Modulus of Rigidity

1.8.2 Transformed Stiffness Matrix [$\bar{Q}$]

To account for different ply orientations within the laminate, the reduced stiffness matrix is transformed to the global coordinate system using the following expressions [25].

$$\bar{Q} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ Q_{12} & Q_{22} & Q_{26} \\ Q_{16} & Q_{26} & Q_{66} \end{bmatrix} \quad (4)$$

Each component is calculated from the original Q matrix and the ply angle θ

$$\bar{Q}_{11}= Q_{11}m^4+2(Q_{12}+2Q_{66})\ m^2n^2+Q_{22}n^4 \quad (4.1)$$

$$\bar{Q}_{12} = (Q_{11}+Q_{22}-4Q_{66})\ m^2n^2+Q_{12}(m^4+n^4) \quad (4.2)$$

$$\bar{Q}_{22} =Q_{11}n4+2(Q_{12}+2Q_{66})m^2n^2+Q_{22}m^4 \quad (4.3)$$

$$\bar{Q}_{16} = (Q_{11}-Q_{12}-2Q_{66})m^3n-(Q_{22}-Q_{12}-2Q_{66})mn^3 \quad (4.4)$$

$$\bar{Q}_{26}=(Q_{11}-Q_{12}-2Q_{66})mn^3-(Q_{22}-Q_{12}-2Q_{66})m^3 \quad (4.5)$$

$$\bar{Q}_{66}=(Q_{11}+Q_{22}-2Q_{12}-2Q_{66})m^2n^2+Q_{66}(m^4+n^4) \quad (4.6)$$

where m= cosθ & n=sinθ

These transformed matrices are calculated for each ply based on its fiber orientation angle θ.

1.8.3 The ABD matrix has three blocks

A: Extensional stiffness matrix (in MPa.mm)

B: Coupling stiffness matrix (in $MPa.mm^2$)

D: Bending stiffness matrix (in $MPa.mm^3$)

A Matrix Structure

This matrix represents the in-plane stiffness of the laminate. It relates in-plane forces (N_x, N_y, N_{xy}) to mid-plane strains (ε_x, ε_y, γ_{xy}) [17]

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} . \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \quad (5)$$

where A_{11}: Stiffness in the x-direction due to strain in the x-direction (analogous to axial stiffness (E_x)

A_{22}: Stiffness in the y-direction due to strain in the y-direction (E_y)

A_{12}: Coupling stiffness between ε_x and N_y or ε_y and N_x (Poisson effect)

A_{66}: Shear stiffness for in-plane shear strain γ_{xy} and in-plane shear force N_{xy} A_{16}: Coupling between axial strain ε_x and in-plane shear force N_{xy} (asymmetry in fiber angle causes this)

A_{26}: Coupling between axial strain ε_y and shear force N_{xy}

1.8.4 Laminate Specifications

The following Combinations were made having 8 layers with total thickness of laminate is 3mm.So thickness will be ply thickness = 3/8= 0.375 mm per ply. The volume fraction calculation presented for the laminate was used to estimate the practical fiber volume fraction achieved during fabrication. The obtained value is 50% fiber volume fraction assumed in the CLT analysis, thereby providing consistency between experimental processing and theoretical modeling.

1.8.5 Laminate Properties

Material properties used in the CLT analysis. Carbon, glass, and Kevlar epoxy ply properties are listed in Table 2.

Table 2. Material properties, [41][42]

Material	E_1(GPa)	E_2 (GPa)	G_{12}(GPa)	ν_{12}
Carbon Fiber	135	10	5	0.28
Glass Fiber	50	15	5	0.28
Kevlar Fiber	76	5	2	0.34
Mild Steel Wire Mesh	200	200	80	0.30

1.9 Fibre Orientation for Hybrid Composite Laminates

The Classical Laminate theory for the laminates will be applied as per fibre orientations and ply thickness and per ply thickness.The values ply orientation and $\bar{Q}$ are given in Table 3 for further calculations.

Table 3. Ply orientation and $\bar{Q}$ values

Ply	Material/Epoxy	θ (deg)	$\bar{Q}_{11}$(MPa)	$\bar{Q}_{12}$ (MPa)	$\bar{Q}_{22}$ (MPa)	$\bar{Q}_{66}$ (MPa)	$\bar{Q}_{16}$ / $\bar{Q}_{26}$ (MPa)
1.	Carbon Fibre	0	135800	2820	10060	5000	0
2.	Kevlar Fibre	0	76580	1710	5040	2000	0
3.	Mild Steel Wire Mesh	+45	222860	62850	222860	76930	0
4.	Mild Steel Wire Mesh	-45	222860	62850	222860	76930	0
5.	Glass	90	15360	4300	51200	5000	0
6.	Mild Steel Wire Mesh	-45	222860	62850	222860	76930	0
7.	Mild Steel Wire Mesh	+45	222860	62850	222860	76930	0
8.	Kevlar Fibre	0	76580	1710	5040	2000	0

Note: $\bar{Q}_{16} = \bar{Q}_{26} = 0$ for all plies (due to symmetry or fiber orientation), so $A_{16} = A_{26} = 0$.
According to above data we will calculate A matrix components.

We compute each component as

1.9.1 Classical Laminate Theory for Laminate1

a. Extensional stiffness Matrix [A]

The equation for A matrix is given as follows:

$$A_{ij} = \sum_{k=1}^{8} Q_{ij}^{k} . (Z_k - Z_{k-1}) \tag{6}$$

So A matrix will be:

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} MPa.mm \tag{7}$$

$$Final\ A\ Matrix = \begin{bmatrix} 446422 & 97800 & 0 \\ 97800 & 392415 & 0 \\ 0 & 0 & 120650 \end{bmatrix} MPa.mm \tag{8}$$

The equation for B matrix is given as follows

b. Coupling Stiffness Matrix [B]

General Equation for B Matrix is given by

$$B_{ij} = \sum_{k=1}^{n} (Q)ij^{(k)} \cdot \frac{1}{2}(z_k^2 - z_{k-1}^2) \tag{9}$$

where $\bar{Q}_{ij}^{(k)}$ is the transformed stiffness matrix component for the k-th ply.

z_k,z_k−1: top and bottom coordinates of the k_{th} ply with respect to the mid-plane

B Matrix (Bending-Extension Coupling Matrix) (MPa.mm^2)

$$B=\begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix}=\begin{bmatrix} -61864 & 0 & 0 \\ 16650 & 61684 & 0 \\ 0 & 0 & 0 \end{bmatrix} MPa.mm^2 \tag{10}$$

c. Bending stiffness Matrix [D]

General Equation for D Matrix is given as follows:

$$[D] = \frac{1}{3} \cdot \sum_{k=1}^{n} \bar{Q}_{ij}^{(k)} (z_k^3 - z_{k-1}^3) \tag{11}$$

D Matrix (Bending stiffness Matrix) (MPa.mm^3):

$$D=\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}=\begin{bmatrix} 208688 & 22484 & 0 \\ 22484 & 160901 & 0 \\ 0 & 0 & 29473 \end{bmatrix} MPa.mm^3 \tag{12}$$

d. Combined ABD Matrix for laminate 1 will be as follows

$$ABD=\begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \tag{13}$$

$$ABD = \begin{bmatrix} 446422 & 97800 & 0 & -61864 & 0 & 0 \\ 97800 & 392415 & 0 & 16650 & 61684 & 0 \\ 0 & 0 & 120650 & 0 & 0 & 0 \\ -61864 & 0 & 0 & 208688 & 22484 & 0 \\ 16650 & 61684 & 0 & 22484 & 160901 & 0 \\ 0 & 0 & 0 & 0 & 0 & 29473 \end{bmatrix} \tag{14}$$

The mechanical response of Laminate 1 is comprehensively characterized by its ABD stiffness matrices, which quantify the in-plane coupling and bending behaviors respectively. The extensional stiffness matrix (A-matrix) shows significant axial and transverse rigidity with A_{11}=446422 MPa.mm. A_{12}=97800MPa.mm, A_{22}=392415 MPa.mm and moderate in-plane shear stiffness A_{66}=120650 MPa.mm. The laminate is asymmetric as the coupling stiffness matrix (B-matrix) shows with B_{11}=-61864 Mpa.mm2, B_{12}=16650 Mpa.mm^2 and B_{22}=61684 Mpa.mm^2 is not zero, with B_{11},-B_{22} showing a high degree of interaction between the laminate and its constituent materials.

The bending stiffness matrix (D-matrix) reveals the out-of-plane resistance with D_{11}=208688 MPa.mm^3,D_{22}=160901 MPa.mm^3 and shear related D_{66}=29473 MPa.mm^3.D_{12}=22484 MPa.mm^3 off-diagonal bending term also suggests the existence of coupling between orthogonal directional bending. The high in-plane stiffness, large coupling effects, and moderate bending rigidity prove the fact that Laminate 1 is anisotropic and asymmetric in behavior characteristic of the hybrid fiber-metal laminates including carbon, Kevlar and mild steel wire mesh layers.

1.9.2CLT Analysis for Laminate 2(GKMS)

The CLT of laminate 2 is determined based on the following mechanical properties that are displayed in Table 4.

Table 4. Material properties [41][42]

Material/Epoxy	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}
Glass Fibre	50	15	5	0.28
Kevlar Fibre	76	5	2	0.34
Mild Steel Wire mesh	200	200	80	0.3

A Matrix for Laminate2 GKMS) (Extensional Stiffness) [MPa.mm]

$$A = \begin{bmatrix} 257103 & 65546 & -3360 \\ 65546 & 216888 & -3360 \\ -3360 & -3360 & 77373 \end{bmatrix} MPa.mm \quad (15)$$

B Matrix (Coupling Stiffness) [MPa.mm^2]

$$B = \begin{bmatrix} -4410 & 1274.9 & -1260 \\ 1274.9 & 18410 & -4410 \\ -1260 & -4410 & -4670.8 \end{bmatrix} MPa.mm^2 \quad (16)$$

D Matrix (Bending Stiffness) [MPa.mm^3]

$$D = \begin{bmatrix} 68030 & 23600 & -160 \\ 23600 & 73680 & -160 \\ -160 & -160 & 25500 \end{bmatrix} MPa.mm^3 \quad (17)$$

Combined ABD Matrix for Laminate2 will be as follows

$$ABD = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \quad (18)$$

$$ABD = \begin{bmatrix} 257103 & 65546 & -3360 & -4410 & 1274.9 & -1260 \\ 65546 & 216888 & -3360 & 1274.9 & 18410 & -4410 \\ -3360 & -3360 & 77373 & -1260 & -4410 & -4670.8 \\ -4410 & 1274.9 & -1260 & 68030 & 23600 & -160 \\ 1274.9 & 18410 & -4410 & 23600 & 73680 & -160 \\ -1260 & -4410 & -4670.8 & -160 & -160 & 25500 \end{bmatrix} \quad (19)$$

Laminate 2 mechanical performance is characterized by the ABD matrices that are the combination of the extensional, bending-extension coupling, and bending stiffness. The A-matrix indicates moderate in-plane stiffness, with A_{11} = 257103 MPa·mm, A_{22} = 216888 MPa·mm, and shear stiffness A_{66}= 77373 MPa·mm. Anisotropy and fiber misalignment of laminates is indicated by the presence of non-zero shear-extension coupling terms like A_{16} = A_{26} = -3360 MPa.mm. The B-matrix further confirms the asymmetry in the laminate's stacking sequence, with non-negligible coupling terms like B_{11} = −4410 MPa·mm², B_{12} = 1274.9 MPa·mm², and B_{22}= 18410 MPa·mm². Additional off-axis coupling, seen in terms such as B_{16} = −1260 MPa·mm² and B_{66} = −4670.8 MPa·mm², indicates strong interactions between in-plane loading and twisting/bending responses. The D-matrix shows the laminate's resistance to bending deformations, with D_{11} = 68030 MPa·mm³, D_{22}= 73680 MPa·mm³, and D_{66} = 25500 MPa·mm³. Off-diagonal entries like D_{12}= 23600 MPa·mm³ and small but non-zero D_{16} = D_{26} = −160 MPa·mm³ reflect orthotropic bending behavior and residual bending-twisting coupling. Taken together, the ABD matrix elements affirm the fact that Laminate 2 behaves anisotopically and asymmetrically structurally, which can be attributed to the fact that the material is a hybrid of glass, Kevlar, and mild steel.

Laminate 2 is anisotropic and asymmetric because of the hybrid building and order. The identified bending-extension coupling and directional stiffness properties show that it can be used in any application that requires control over deformation and customized mechanical behavior.

2. Results

The mechanical analysis of two hybrid laminates Carbon/Kevlar/Mild Steel wire mesh (Laminate 1) and Glass/Kevlar/Mild Steel wire mesh (Laminate 2) was carried out using Classical Laminate Theory with detailed computation of the ABD stiffness matrices. The extensional stiffness (A-matrix) revealed significantly higher values for Laminate 1, including A_{11}=446,422 MPa·mm and A_{22}=392,415 MPa·mm compared to Laminate 2 values of A_{11}=257,103 MPa·mm and A_{22}=216,888MPa·mm. Similarly, shear stiffness $A_{66}$was higher in Laminate 1(120,650 MPa·mm) than in Laminate 2 (77,373 MPa·mm).

The B-matrix analysis showed non zero coupling for Laminate 1 which is asymmetric, whereas Laminate 2 displayed moderate coupling with B_{12}=1274.9 MPa·mm² and notable non-zero B_{16} and B_{26} values. The bending stiffness (D-matrix) further confirmed the best flexural behavior of Laminate 1 with D_{11}=208,688 MPa·mm³ and D_{22} =160,901 MPa·mm³ compared to 68,030 MPa·mm³ and 73,680 MPa·mm³ for Laminate 2.

Modulus derivations from these matrices showed that Laminate 1 achieved tensile moduli of E_f^x =148.81GPa and E_f^y =130.8 Gpa.The flexural moduli of 92.75GPa and 71.51GPa for laminate 1 & 2 respectively and a shear modulus of 40.22GPa. In contrast, Laminate 2 yielded 25.79 GPa. These results demonstrate that Laminate 1 consistently exhibits best mechanical properties, attributed primarily to the incorporation of high-stiffness carbon fibers. Visual comparisons using line graphs further validated this performance distinction, with Laminate 1 displaying greater stiffness anisotropy and higher modulus values in all principal directions. On balance, Laminate 1 is more applicable in the use of large strength to weight ratios, rigidity, and dimensional stability involving complicated loading situations.

2.1 Comparative Evaluation of Laminate 1 and Laminate 2

The analysis is on the basis of three matrices that are A, B& D matrix that are further compared.

2.1.1 Extensional Behavior (A-Matrix)

The extensional stiffness matrix [A] is used to indicate the in-plane mechanical behavior of the laminates. The carbon and Kevlar in the 0^0 and 90^0 orientation give Laminate 1 (CKMS) higher values of axial stiffness, higher values of A12 and A66, higher longitudinal-transverse coupling, and higher in-plane shear strength. Laminate 2 (GKMS), a woven material made of a combination of glass and Kevlar, is more isotropic and balanced in-plane stiffness profile. Although Laminate 2 offers a medium performance on axial, the symmetric orientation of the fibers and the choice of materials helps to achieve the equal distribution of the loads and a less brittle type of failure.

Laminate 1, therefore, has a high in-plane stiffness profile, which is important when using the axial load-dominated constructions. Figure 7 represents the comparison of A matrix.

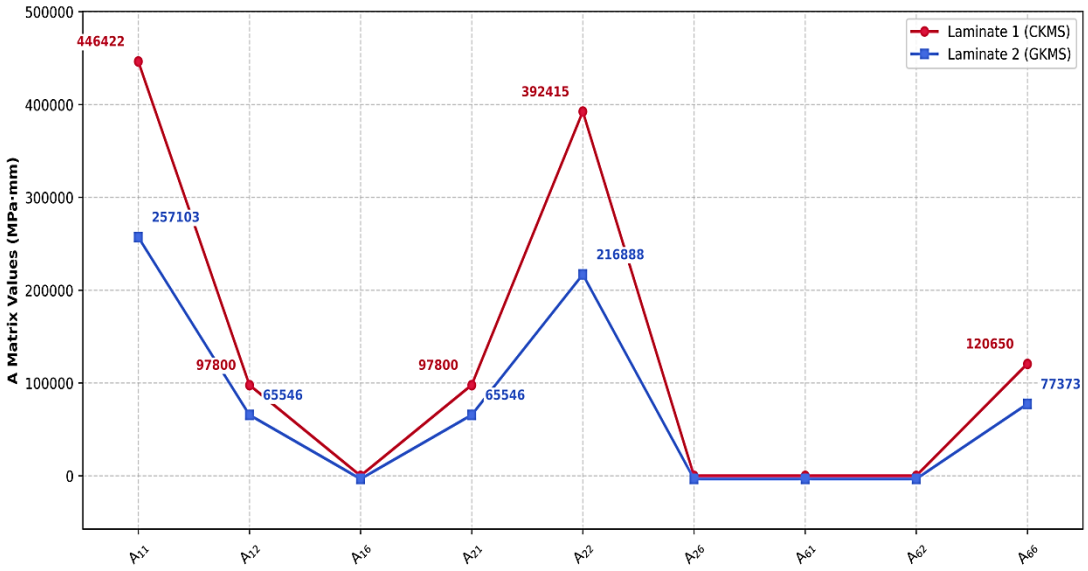

Fig. 7. - In-Plane Stiffness (A matrix) of CKMS and GKMS Laminates.

2.1.2 Coupling Behavior (B-Matrix)

The bending extension coupling characteristic due to laminate asymmetry is given by the [B] matrix. In B_{11}, B_{12}, B_{22} and B_{66}, Laminate 1 has an important value of non-zero numbers, indicating that the Bending interaction of extensions is strong. This is because of the non-symmetric stacking order as well as the heterogeneous distribution of materials. The moderate B_{11}, dominant B_{22}, non-zero B_{16},B_{26} terms refer to the extension bending and extension twisting interactions, especially at the transverse direction. In comparison to Laminate 1, Laminate 2 has lower yet not negligible coupling which offers a trade-off between tailoring of deformation and structural integrity. Thus, though

Laminate 1 is focused on the promotion of the coupling behavior, Laminate 2 provides a relatively controlled coupling with a better load-bearing stability during the multidirectional loading. B matrix values comparison is indicated in Table 8.

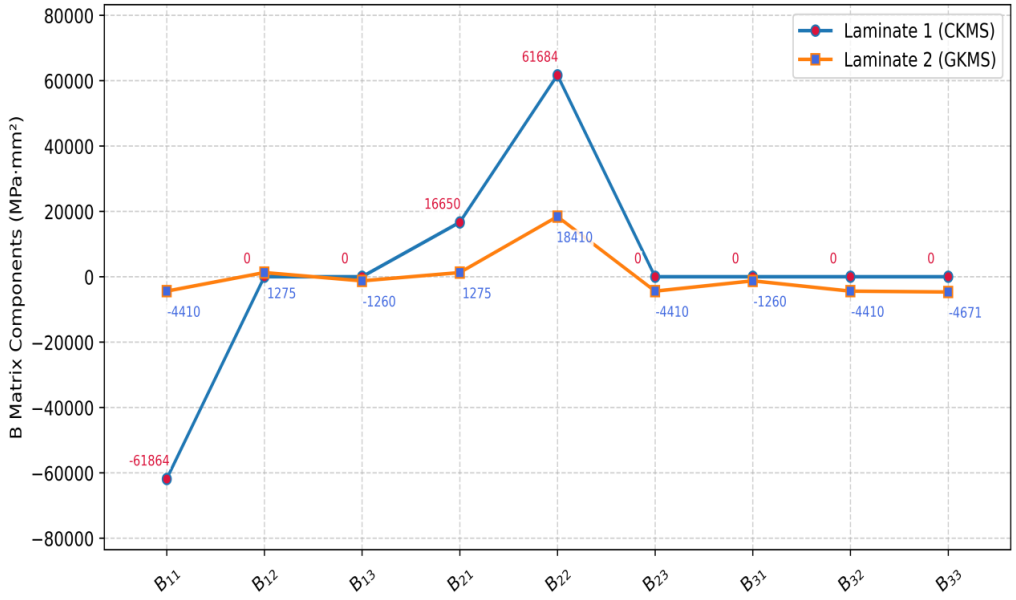

Fig.8. - Distribution of Coupling Stiffness (B- Matrix) Components for CKMS & GKMS Laminates

2.1.3Bending Behavior (D-Matrix)

The out of plane rigidity of the laminates can be determined through bending stiffness (the [D] matrix). Laminate 1 exhibits significantly greater bending stiffness because the outer layers have carbon fibers and therefore are associated with higher values of D_{11} and D_{22}. This causes it to be extremely resistant to flexural deformations. On the one hand, Laminate 2 is less rigid in bending terms, but the performance of the material is average, as the material incorporates +-45^0 mild steel plies and woven glass plies. Its design is also more ductile and damage tolerant to flexural loads, and it is therefore appropriate in areas that demand energy absorption and flexibility.

Therefore, Laminate 1 offers greater flexural rigidity and Laminate 2 is more bend tolerant and ductile. Figure 9 represents the comparison of B matrix values.

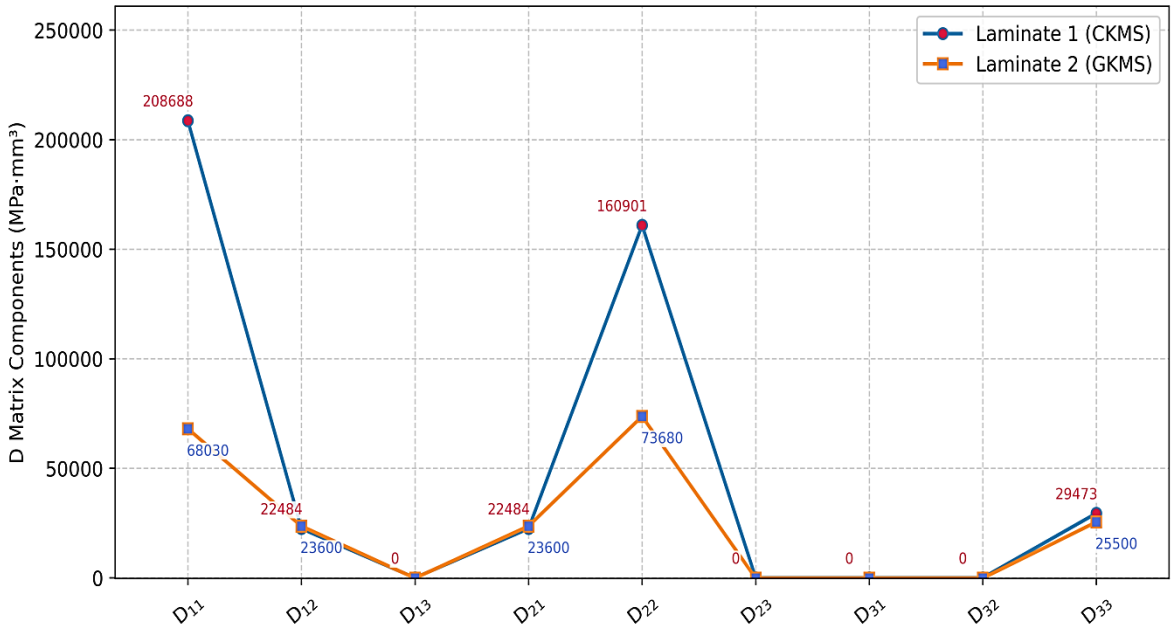

Fig. 9. - Bending Stiffness (D-Matrix) Component Characteristics of CKMS & GKMS Laminates

2.1.4 Overall ABD Comparison for Laminate 1 and Laminate 2

Comparison analysis of the ABD matrices obviously indicates that Laminate 1 is better than Laminate 2 in the fields of extensional, coupling and bending. Laminate 1 has an advantage in high-modulus carbon fibers and asymmetry, which increase the stiffness, coupling properties, and shear resistance. Otherwise, Laminate 2 is less expensive, symmetric, and provides enough in-plane rigidity, low coupling behavior and reasonable bending rigidity. In short, Laminate 1 is designed to be used in high-performance structural applications, whereas Laminate 2 offers performance tradeoff on both cost-sensitive and flexible composite applications. The combined ABD matrix values for laminate 1 & laminate 2 is represented in Figure 10.

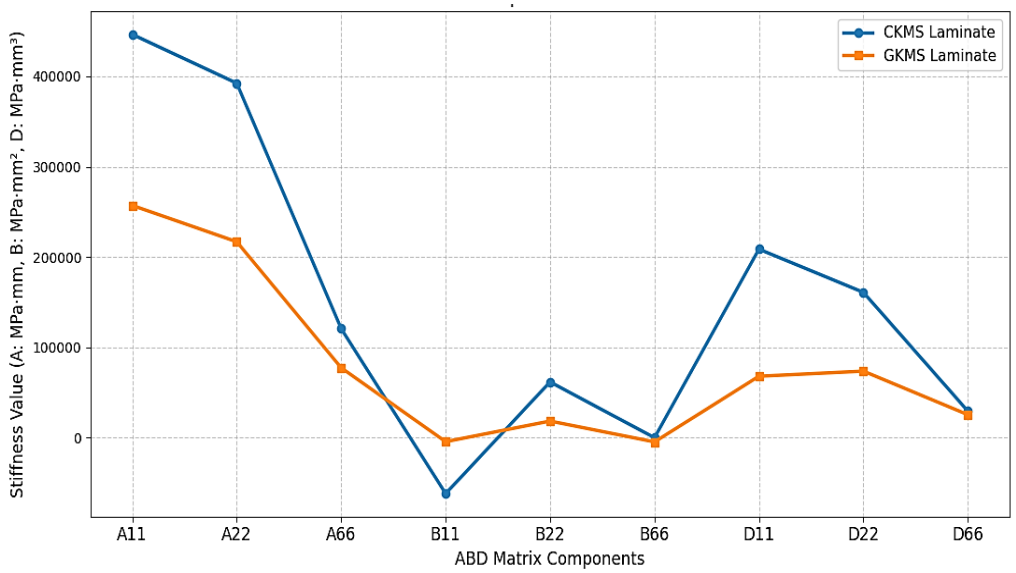

Fig. 10. Variation of ABD Stiffness Components for CKMS & GKMS Laminates

2.2 Flexural Modulus

The calculations for flexural modulus for laminate 1 and 2 are given as follows

2.2.1For Laminate1 (CKMS)

For calculating flexural modulus values of D matrix were utilized which are represented in Table 5.

Table 5. D matrix values for calculation of flexural modulus for Laminate1

Direction	D Value (MPa·mm³)	Flexural Modulus E_f(GPa)
X (D_{11})	208,688	92.75 GPa
Y (D_{22})	160,901	71.51 GPa

The flexural modulus of Laminate 1 was computed from the D matrix using the classical relation

$$E_f^x = \frac{12D11}{h^3} = \frac{12x208688}{3^3} = 92750\ Mpa = 92.75\ GPa \quad (20)$$

$$E_f^y = \frac{12D22}{h^3} = \frac{12x160901}{3^3} = 71511.5\ Mpa = 71.51\ GPa \quad (21)$$

2.2.2 Flexural Modulus for Laminate2 (GKMS)

For calculating flexural modulus we need values of D matrix which are represented in Table 6.

Table 6. D matrix values for calculation of flexural modulus for Laminate 2

Direction	D Value (MPa·mm³)	Flexural Modulus E_f(GPa)
X (D_{11})	68,030	30.24
Y (D_{22})	73,680	32.75

Similarly for laminate2 the modulus in the longitudinal direction was computed as 30.24 GPa, while the transverse modulus was 32.75 GPa.

$$E_f^x = \frac{12D11}{h^3} = \frac{12x68030}{3^3} = 30.24\ GPa \quad (22)$$

$$E_f^y = \frac{12D22}{h^3} = \frac{12x73680}{3^3} = 32.75\ GPa \quad (23)$$

2.2.3 Flexural Modulus Comparison

The flexural modulus comparison for both laminates is given in Table 7.

Table 7. Flexural Modulus Comparison

Laminate	E_f (GPa) X Direction	E_f(GPa) Y Direction
(Carbon/Kevlar/MS)	92.75	71.51
(Glass/Kevlar/MS)	30.24	32.75

The graph for comparison of Flexural modulus is represented in Figure 11.

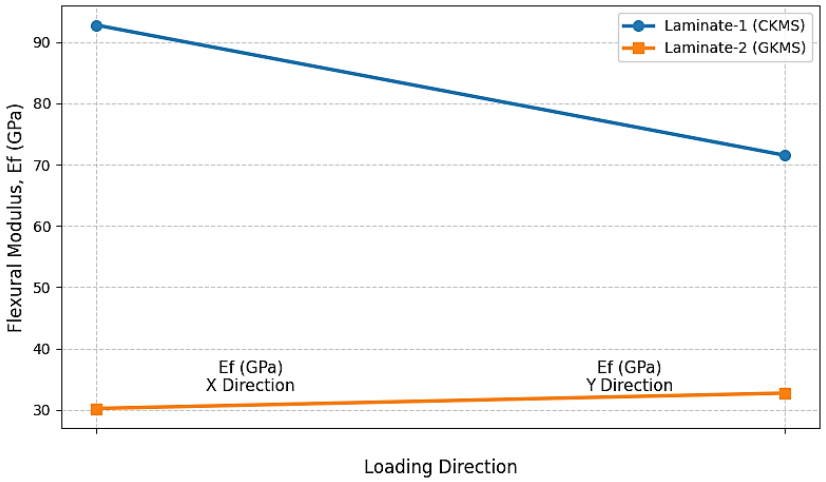

Fig. 11. Flexural Modulus Comparison between CKMS and GKMS

The flexural module of both hybrid laminates were derived from their respective bending stiffness matrices using the Classical Laminate Theory (CLT) (Aklilu et al., 2024) .As shown in the comparative table, Laminate 1 (Carbon/Kevlar/Mild Steel wire mesh) exhibits substantially higher flexural rigidity in both the longitudinal and transverse directions, with values of 92.75 GPa and 71.51 GPa, respectively. These values are more than double those of Laminate 2 (Glass/Kevlar/Mild Steel wire mesh), which recorded 30.24 GPa and 32.75 GPa in the same directions. This pronounced difference is primarily attributed to the higher modulus of carbon fibers and the optimized hybrid stacking sequence used in Laminate 1, which significantly enhances its resistance to out-of-plane bending. On the other hand, Laminate 2 has lower values, which is suggestive of less stiffness provided by glass fibers, hence it is less stiff when it comes to bending loads. This comparative analysis shows clearly the mechanical capability of Laminate 1 over structural usage which requires greater flexural performance which is applied in the aerospace panel, composite shafts and high load carrying components.

2.3Tensile Modulus

The calculations for tensile modulus for laminate 1 and 2 are given as follows

2.3.1Tensile Modulus for Laminate1 (CKMS)

For calculating tensile modulus for laminate 1, we need A matrix values which are represented in Table 8

Table 8. A matrix values for calculation of tensile modulus for laminate 1

Direction	A11/A22 (MPa·mm)	E_f (GPa)
Longitudinal (X)	446,422	148.81
Transverse (Y)	392,415	130.81

The tensile modulus of Laminate 1 was computed from the A matrix using the classical relation

$$E_f^x = \frac{A11}{h} = \frac{446422}{3} = 148.81 \text{ GPa} \quad (24)$$

$$E_f^y = \frac{A22}{h} = \frac{392415}{3} = 130.81 \text{ GPa} \quad (25)$$

2.3.2 Tensile Modulus for Laminate2

For calculating tensile modulus for laminate 2 we need A matrix values which are represented in Table 9

Table 9. A matrix values for calculation of tensile modulus for laminate 2

Direction	A11/A22(MPa·mm)	E_f (GPa)
Longitudinal (X)	257,103	85.70
Transverse (Y)	216,888	72.30

$$E_f^x = \frac{A11}{h} = \frac{257103}{3} = 85.70\ GPa \quad (26)$$

$$E_f^y = \frac{A22}{h} = \frac{216888}{3} = 72.30\ GPa \quad (27)$$

2.3.3Tensile Modulus Comparison

The tensile modulus for laminate 1 and are compared and represented in Figure 12.

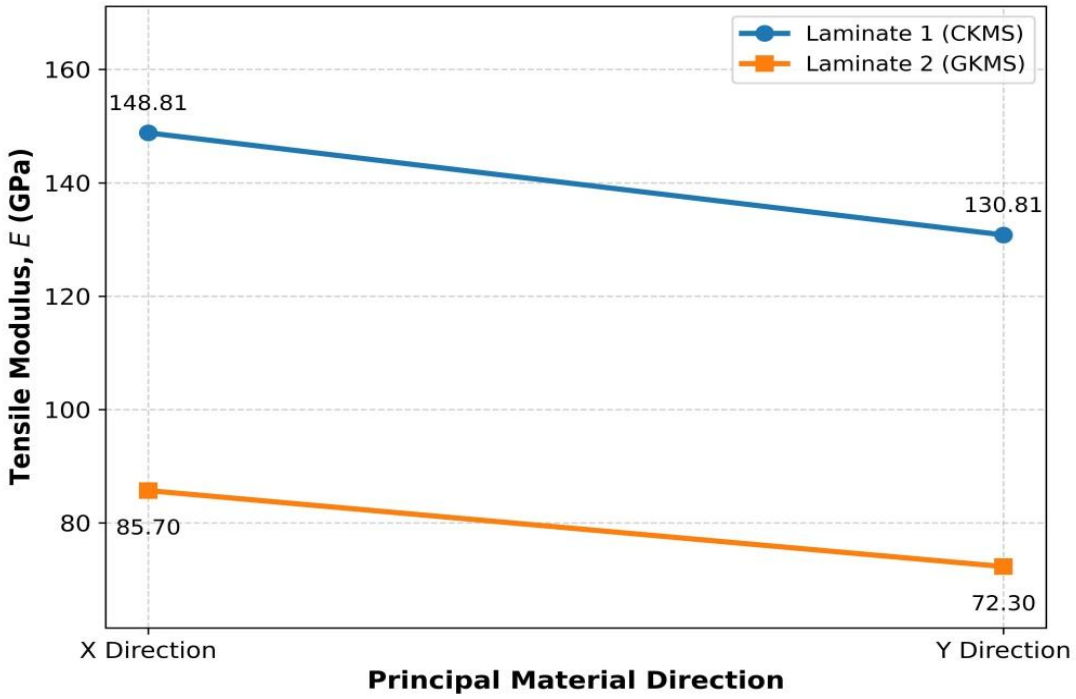

Fig. 12. Directional Tensile Modulus Characteristics of CKMS & GKMS

The in-plane tensile moduli of both laminates were computed from the extensional stiffness (A) matrices using the values A_{11} and A_{22} with thickness of 3mm.Laminate 1 (Carbon/Kevlar/Mild Steel wire mesh) exhibited significantly higher tensile moduli in both principal directions, with values of 148.81 GPa in the longitudinal (X) direction and 130.81 GPa in the transverse (Y) direction. In contrast, Laminate 2 (Glass/Kevlar/Mild Steel wire mesh) showed reduced moduli of 85.70 GPa and 72.30 GPa in the respective directions. These results clearly illustrate the superior in-plane load-carrying capacity and stiffness of Laminate 1, primarily due to the inclusion of high-modulus carbon fibres. The composite Laminate 2 has reduced stiffness because of lower modulus of glass fibres and the high compliance as a result of the greater extensional coupling. In general, the tensile comparison study affirms that Laminate 1 is more structurally efficient when it comes to objects that demand high tensile rigidity e.g. drive shafts, structural skins, and automotive panels.

2.4 Shear Modulus

We obtain the in-plane shear modulus (G_{12}) of the laminate by multiplying the shear stiffness of the A 6 term of the extensional stiffness matrix [A] and the overall laminate thickness h.

2.4.1Shear Modulus for Laminate1

The shear modulus for laminate 1 is calculated by considering values of A matrix listed in Table 10.

Table 10. A matrix values for calculation of shear Modulus

Laminate	A_{66} (MPa·mm)	Thickness h (mm)	G_{12} (GPa)
(Carbon/Kevlar/MS)	120,650	3.0	40.22
(Glass/Kevlar/MS)	77,373	3.0	25.79

$$G_{12} = \frac{A66}{h} = \frac{120650}{3} = 40.22\ GPa \quad (28)$$

Similarly for laminate2

$$G_{12} = \frac{A66}{h} = \frac{77373}{3} = 25.79\ GPa \quad (29)$$

2.4.2Comparison of Shear Modulus

The shear modulus comparison for laminate 1 and 2 is represented in Figure 13.

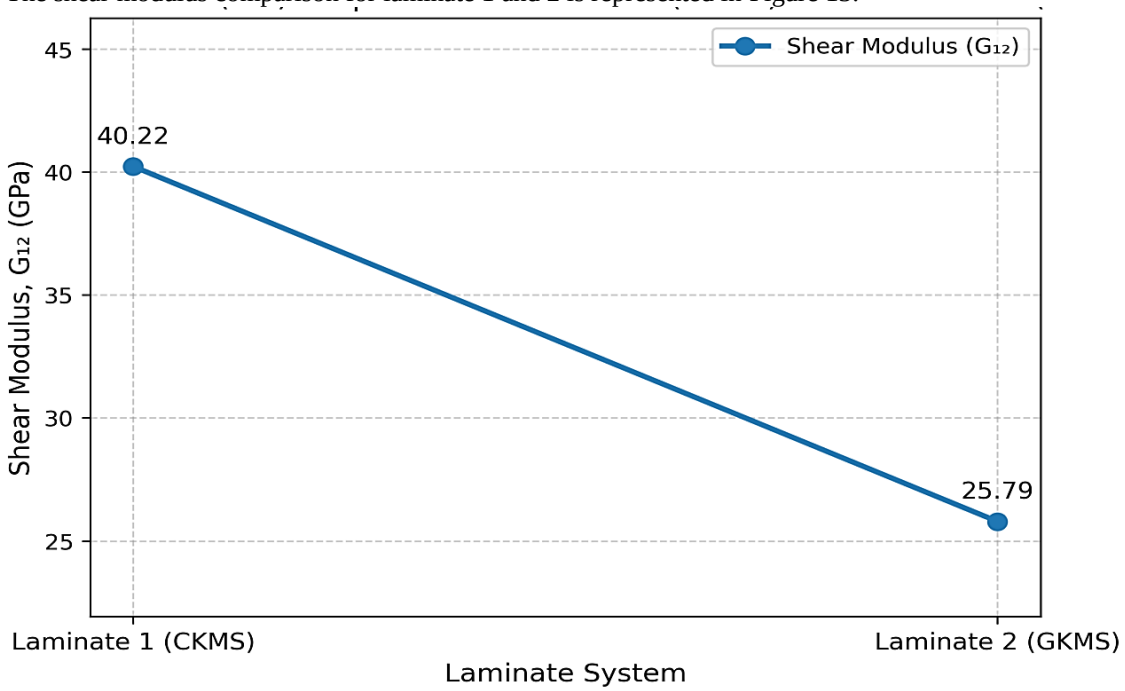

Fig. 13. Shear Modulus (G_{12}) Response of CKMS& GKMS

The in-plane shear modulus $G_{xy}$was calculated for both laminates using the shear stiffness term $A_{66}$from the extensional stiffness matrix. Laminate 1 reinforced with carbon fibers exhibited a significantly higher shear modulus of 40.22 GPa compared to 25.79 GPa for Laminate 2. This reflects the superior resistance of Laminate 1 to in-plane distortion under torsional or shearing loads, owing to the high stiffness characteristics of carbon fibers. The lower shear stiffness in Laminate 2 results from the relatively lower modulus of the glass fibers which, while improving compliance and damping, may limit its use in applications where high shear rigidity is critical.

2.5 Comparison of CLT Predictions

2.5.1 Flexural Modulus

[31] reported that D type composite Carbon/Glass/Kevlar/Carbon/Kevlar/Glass/Carbon [CGKCKGC] flexural strength of 380.96 MPa and Modulus of 36.52GPa respectively. In the present study, the Glass/Kevlar/Mild Steel (GKMS) laminate exhibited flexural moduli in the range of 30.24 & 32.75 GPa, In contrast, the Carbon/Kevlar/Mild Steel (CKMS) laminate demonstrated substantially higher flexural moduli of 71.51 &92.75 GPa. This has been mainly improved by the use of high-modulus carbon fibers and mild steel wire mesh which is much more effective in reducing bending stiffness. By these findings, it is confirmed that the CLT-based predictions are correlated with the reports made of hybrid composite systems previously and it distinctly indicates the increment in stiffness through the optimum hybridization of a fiber-metal composite.

2.5.2 Tensile Modulus

According to [32], tensile modulus values of E-glass/epoxy (GFRP) were 38 Gpa when stacked in order of 159 Gpa when stacked in order of carbon/epoxy (CFRP). The tensile moduli of 72.30 and 85.70 GPA of the GKMS laminate used in the current work are within the range of tensile moduli of glass-dominated hybrid composites. Tensile moduli of CKMS laminate were higher 130.81 &148.81 Gpa, which is near to the upper limits of carbon-based hybrid laminates reported by [32]. This confirms the tensile modulus predictions obtained through Classical Laminate Theory and puts to the fore the usefulness of carbon fiber integration to improve axial stiffness.

2.5.3 Shear Modulus

[30] gave an in-plane shear modulus (0deg/90deg) and (+-45deg) values of 10.3 or 11.5 Gpa (pure carbon-epoxy woven composites). Comparatively, the current hybrid laminates had very high effective shear moduli of 40.22Gpa of the Carbon/ kevlar/ Mild Steel laminate and 25.79 Gpa of the Glass/ kevlar/ Mild Steel laminate, which

were determined using CLT (A 6/ h). This high increment is explained by the fact that it has +-45deg mild steel wire mesh-layers, which is a significant contributor to the laminate shear stiffness. These findings are physically in line with a laminate architecture and theoretical framework, used [30].

3. Limitations of the Current Research

3.1 Assumptions

The current analysis is founded on Classical Laminate Theory (CLT) and presupposes that there will be no interfacial slip, no de-lamination, no de-bonding, and that bonding between the adjacent laminate is perfect. The laminas are assumed to be all homogeneous, orthotropic and linearly elastic. The formulation also assumes that the strains and the deformations are small across the laminate.

3.2 Simplifications

Transverse shear deformation and thickness stretching effects are neglected in accordance with classical laminate assumptions. Material properties are assumed to be uniform within each ply and are adopted from literature sources. Environmental effects such as temperature variation, moisture absorption, and time-dependent behavior are not considered in the present model.

3.3 Potential Sources of Error

Potential sources of error include manufacturing-induced imperfections such as fiber misalignment, voids, and residual stresses, as well as uncertainties in laminate thickness and ply orientation. Experimental measurement inaccuracies and testing-machine compliance may also lead to deviations between analytical predictions and actual structural behavior. However, due to its linear elastic and perfect bonding assumptions, CLT cannot capture interfacial damage between the mild steel wire mesh and the fibers, plasticity of the steel layer under high strain levels, or out-of-plane shear effects in relatively thick hybrid laminates. These behaviors are important for detailed failure and post-elastic analysis and can be addressed in future work using nonlinear and higher-order modeling approaches

4. Discussion

The CLT-based analysis shows that the (CKMS) laminate consistently exhibits higher extensional, bending, tensile, and shear stiffness than the (GKMS) laminate. This improvement is mainly due to the high elastic modulus of carbon fibers and their contribution to load transfer in both in-plane and out-of-plane directions. The non-zero B-matrix terms observed in CKMS indicate extension bending coupling caused by laminate asymmetry& also observed in GKMS asymmetric stacking. Mild steel wire mesh inclusion contributed greatly to the shear stiffness of both laminates resulting in high in-plane shear moduli unlike the traditional fiber-only composites. Also values are validated.

5.Practical Implications

This study gives the results which could be used as a quantitative criterion on informed selection of material as well as laminate structure in high performance engineering. The practical implications are made as a result of the mechanical analysis on the Carbon/Kevlar/Steel (Laminate1) and Glass/Kevlar/Steel (Laminate2).

5.1 Educating Material Choice of Structural Components of Rigidity.

The study proves that Laminate 1 possesses a longitudinal flexural modulus of 92.75 Gpa, more than three times than the one of Laminate 2 of 30.24 Gpa. This brings out the fact that on the aerospace panels, car-chassis, or car load-bearing components, where stiffness-to-weight ratio is extremely important, it is the responsibility of engineers to consider carbon-reinforced hybrid configurations.

5.2 Impact and Damage Tolerance User Design:

Kevlar fibers and mild steel wire mesh through the integration of both laminates helps to provide toughness and shear ductility. In high-dynamic loading/impact scenarios such as defense armor or marine hulls the synergy between high-strength fibers and ductile steel mesh enables a best-case scenario, known as a fail-safe design, where loads are distributed and catastrophic brittle failure is avoided.

5.3 Cost-Effective and Ductile Design Decisions:

Although Laminate 2 is less stiff, the glass-based architecture offers a more balanced in-plane stiffness profile and much reduced material prices. In the industry, where rigidity is not the main consideration because of cost considerations and where energy absorption e.g. general-purpose protective covers Laminate 2 can be used as a replacement of costly all-carbon systems.

5.4 Exploiting Stacking Sequences to Structural Stability:

It is pointed out in the study that stacking sequences directly control the bending-extension coupling with Laminate 1 showing a large value B_{11}=-61,864 MPa.mm^2 and Laminate 2 having asymmetric arrangement with almost zero coupling. On the other hand, the coupling characteristic of Laminate 1 can be deliberately exploited to create smart structures, which would have customized deformation characteristics under the condition of axial loading.

Conclusion

The overall analytical examination of two advanced hybrid composite laminates Carbon/Kevlar/Mild Steel Wire Mesh (Laminate 1) and Glass/Kevlar/Mild Steel Wire Mesh (Laminate 2) showed that the type of fiber and the hybridization strategy impacted greatly on the in-plane and out-of-plane stiffnesss. The Classical Laminate Theory allowed derivation of the ABD stiffness matrices to allow systematic quantification of the extensional, coupling, and bending behaviors. The theoretical values of the moduli of elasticity proved the high quality of mechanical performance of Laminate 1, which has about 74 percent higher tensile and flexural modulus of elasticity in the main directions than Laminate 2.

Besides, the visualizations used in MATLAB were useful in comparative interpretation to give a good graphical framework of design-oriented decision-making. Overall, the findings underscore the critical role of hybridization and stacking sequence optimization in tailoring mechanical performance and establish the present study as a valuable reference for the design of lightweight, high-stiffness structural components in aerospace, automotive, and energy applications.

Conflict of Interest

The authors declare that they have no financial or personal conflicts of interest that could have affected the research presented in this article.

AI Disclosure

During the preparation of this work the author did not use any AI tool for writing the content. The author will take full responsibility for content of the publication.

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