Mechanical Behaviour Of Hybrid Composites Under Unidirectional Force: Influence Of Fiber Orientation, Hybrid Structure

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Abstract: This research is about the mechanical properties of hybrid composites with regard to unidirectional loading, taking into account the impact of interweaving designs and fibre alignments. Different stress distribution as well as displacement patterns indicate the significance of material design in optimising performance. The findings show that diverse arrangements in terms of fibre orientations and hybrid configurations can increase tensile strength and energy absorption, giving important information for improving engineering materials.

Keywords: Hybrid composites, Fiber orientation, Unidirectional force, Mechanical behaviour, Stress distribution, Hybrid structure, Composite materials, Tensile strength, Displacement behaviour, Composite configuration

1. INTRODUCTION

1.1 Background

Hybrid composites are an essential part of contemporary engineering applications since they have customised combinations of toughness, strength and durability. For example, carbon-glass-boron (CGB), boron-carbon-glass (BCG), and glass-boron-carbon (GBC) are various forms of carbon fibre, boron fibre and fiberglass configurations that make up composites with different mechanical properties. Understanding the displacement behaviour of these materials under unidirectional loading is crucial for optimising their performance.

1.2 Objective

The aim of this study is to examine the mechanical responses of hybrid composites experiencing uniaxial stress with focus on geometric configuration (CGB, BCG, GBC), fibre orientation and hybrid structure. This research is valuable for optimal configurations in practical engineering applications; it helps analyse stress distribution and displacement thereby giving an insight into material configuration optimisation in composite systems for designing real engineering structures.

1.3 Literature Review

The mechanical behaviour of hybrid composites under unidirectional force during fracture has been extensively studied. For instance, Singh and Singh (2009) have carried out research on the mechanical properties of hybrid composite laminates with different stacking configurations which highlighted the importance of orientation of fibres in determining the mechanical performance of such laminates. This work focuses on the effect(s) that different fibre orientations and hybrid structure(s) have on the behaviour of materials.

Jang et al. (2014) have also done studies that examined flexural and tensile properties of hybrid composites containing carbon and glass fibres. It was found that these hybrid composites are largely influenced by both fibre orientation as well as their structural design on their mechanical strength and stiffness. On this note, Kumar and Lal (1998) investigated fatigue behaviour based on various fibre orientations in order to establish how effective cyclic loading is for a particular material.

The mechanical behaviour of such composites is closely connected with fibre orientation, and the researchers have shown that this relationship can be exploited to improve structural integrity and performance. Controversially, the mechanical properties of hybrid-composite beams were also investigated by Tripathi et al., who examined how various fibre orientations and hybrid compositions affected the beams' load-bearing capacities as well as their deformation characteristics.

The interactions between fibre orientations, failure modes and hybrid structures are complex in hybrid composites under different stress conditions, which have been outlined while discussing the mechanical properties and failure characteristics by Sharma et al. Furthermore, Ilyas et al. has analysed the mechanical properties of hybrid composite materials systematically; they have provided a comprehensive understanding on how these response to external forces changes with varying fibre orientations and hybrid structures present.

Moreover, Kumar and Chand's analyse on the hybrid composites for structural purposes has provided useful insights into mechanical properties and fracture behaviour. Furthermore, Sharma et al.'s experiments have elucidated the fibre orientation and hybrid topologies effects on material stiffness and strength.

The mechanical properties of glass/epoxy and carbon/epoxy hybrid composites have been investigated by Tripathi et al., who also compared different hybrids with varying compositions and fibre orientations. In another study Kumar et al. revealed that hybrid structure and fibre orientation significantly influence the overall mechanical performance of hybrid composites.

2. METHODOLOGY

2.1 Materials and Geometric

In this examination, a composite plate having dimensions of 50 mm by 20 mm was used as geometric model. The plate contained nine layers each having a thickness of 0.125 mm. There were three distinct composition types:

- **CGB**: Carbon Epoxy, Glass Epoxy, Boron Epoxy
- **BCG**: Boron Epoxy, Carbon Epoxy, Glass Epoxy
- **GBC**: Glass Epoxy, Boron Epoxy, Carbon Epoxy

2.2 Experimental Setup

Simulations: Hybrid composite materials' mechanical behaviour was analysed using Abaqus software under controlled environment.

Boundary Conditions: Embedding was applied to one side of the composite sample.

Loading: A unidirectional force was applied to the opposite side F=100N.

This setup allows investigation of stress distribution, deformation patterns and kinematic behaviour under such loading conditions, which gives a better understanding of composites' mechanical performance.

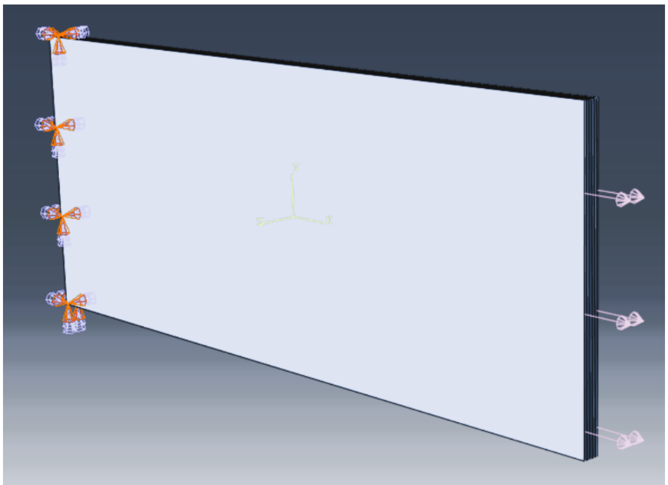

Figure 1. Geometric Model

2.3 Properties

Table 1. Properties of BoronEpoxy, GlassEpoxy, CarboneEpoxy

Property	BoronE	GlassE	CarbonE
Density	2.6×10^{-9}	2.0×10^{-9}	1.6×10^{-9}
Young's Modulus (E)	E_x=210000 MPa	E_x=50000 MPa	E_x=135000 MPa
	E_y=18000 MPa	E_y=12000 MPa	E_y=10000 MPa
	E_z=18000 MPa	E_z=12000 MPa	E_z=10000 MPa
Poisson's Ratio (ν)	$\nu_{xy}=0.3$	$\nu_{xy}=0.25$	$\nu_{xy}=0.3$
	$\nu_{yz}=0.3$	$\nu_{yz}=0.25$	$\nu_{yz}=0.3$
	$\nu_{zx}=0.3$	$\nu_{zx}=0.25$	$\nu_{zx}=0.3$
Shear Modulus (G)	G_{xy}=6000 MPa	G_{xy}=4500 MPa	G_{xy}=5000 MPa
	G_{yz}=6000 MPa	G_{yz}=4500 MPa	G_{yz}=5000 MPa
	G_{zx}=6000 MPa	G_{zx}=4500 MPa	G_{zx}=5000 MPa
Thermal Expansion Coefficients	$\alpha_x=4\times10^{-6}$ 1/°C	$\alpha_x=5\times10^{6}$ 1/°C	$\alpha_x=-1\times10^{-7}$ 1/°C
	$\alpha_y=25\times10^{-6}$ 1/°C	$\alpha_y=30\times10^{-6}$ 1/°C	$\alpha_y=3\times10^{-5}$ 1/°C
	$\alpha_z=25\times10^{-6}$ 1/°C	$\alpha_z=30\times10^{-6}$ 1/°C	$\alpha_z=3\times10^{-5}$ 1/°C
Hashin Damage	T_{1u}=2000 MPa	T_{1u}=1200 MPa	T_{1u}=1500 MPa

	T_{1c}=1500 MPa	T_{1c}=800 MPa	T_{1c}=1500 MPa
	T_{2u}=80 MPa	T_{2u}=50 MPa	T_{2u}=60 MPa
	T_{2c}=200 MPa	T_{2c}=150 MPa	T_{2c}=200 MPa
	T_{6u}=100 MPa	T_{6u}=90 MPa	T_{6u}=80 MPa
	T_{6c}=100 MPa	T_{6c}=90 MPa	T_{6c}=80 MPa
Damage Evolution	D_0=1.0	D_0=1.0	D_0=1.0

2.4 Method of Analysis

Three curves were used to depict the changes in fibre directionality for three hybrid composites (CGB, BCG, GBC). The graphs show how each material behaves mechanically and deforms as well as the kinematic changes along the X and Z axes change due to application of load upon them. This visualisation distinguishes between the respective performances of these structures when subjected to unidirectional forces.

3. RESULTS

3.1 CGB Hybrid Composite:

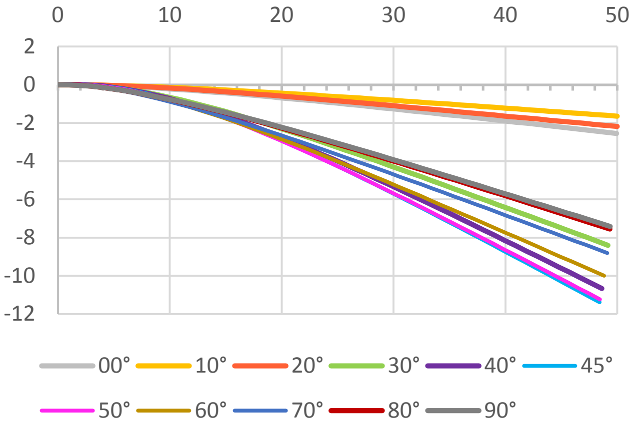

Figure 2. Deformation of CGB composite for various fibre orientations

Table 2. Impact of the CGB's orientation fibre on RF and Extension

Orientation	Extension (mm)	Reaction force (N)
0°	50.00259	40.22
10°	50.02431	42.57
20°	50.03884	47.66
30°	49.96606	92.55
40°	49.92857	82.54
45°	49.91782	77.68
50°	49.91946	70.71
60°	49.94078	62.55
70°	49.95434	59.32
80°	49.96046	48.53
90°	49.96036	46.34

Analysis of the CGB composite configuration under unidirectional force provides valuable insights. The 30° direction offers the highest reaction force (92.55 N) with moderate deformation, making it suitable for applications needing high strength and rigidity. The 40° direction also performs well, with a significant reaction force (82.54 N) and low deformation. While the 10° direction exhibits the minimal deformation, its reaction force (42.57 N) is substantially lower compared to 30° and 40°. Higher angles, such as 90°, show lower reaction forces (46.34 N) and higher deformation, indicating less rigidity. Therefore, the 30° direction is optimal for achieving minimal distortion with a stronger reaction force, while the 40° direction provides a viable alternative.

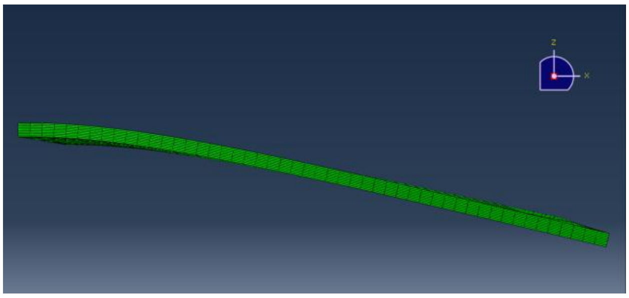

Figure 3. CGB displacement outcome at 30°

3.2 BCG Hybrid Composite

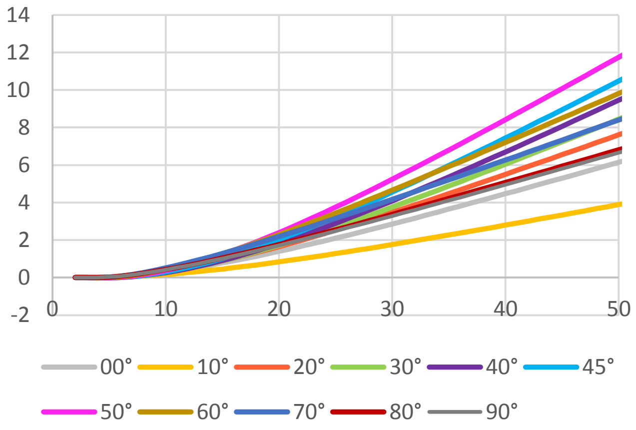

Figure 4. Deformation of BCG composite for various fibre orientations

Table 3. Impact of the BCG's orientation fibre on RF and Extension

Orientation	Extension (mm)	Reaction force (N)
0°	50.14588	121.20
10°	50.10334	71.87
20°	50.18692	119.50
30°	50.21642	97.21
40°	50.24478	76.26
45°	50.26558	74.61
50°	50.28998	75.64
60°	50.23527	60.48
70°	50.20268	57.32
80°	50.16717	44.16
90°	50.16311	42.06

Analysis of the BCG composite configuration under unidirectional force reveals that the 0° direction provides the highest reaction force (121.2 N) and the lowest deformation, making it ideal for applications requiring maximum rigidity and bearing capacity. The 20° orientation also shows adequate performance with high reaction force (119.5 N) and moderate deformation. Although the 10° direction has the lowest level of deformation, it does not provide the same level of reaction force (71.87 N) as the 0° and 20° directions. Higher angles, especially 90°, show the lowest reaction force (42.06 N) and higher deformation, indicating a more elastic behaviour. Therefore, the 0° direction is optimal for applications that need less distortion with stronger feedback, while the 20° direction provides a balanced alternative.

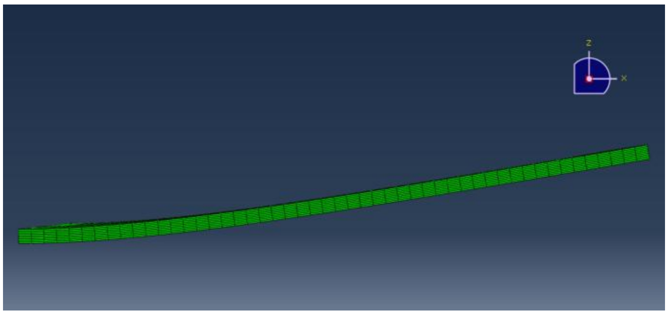

Figure 5. BCG displacement outcome at 0°

3.3 GBC Hybrid Composite:

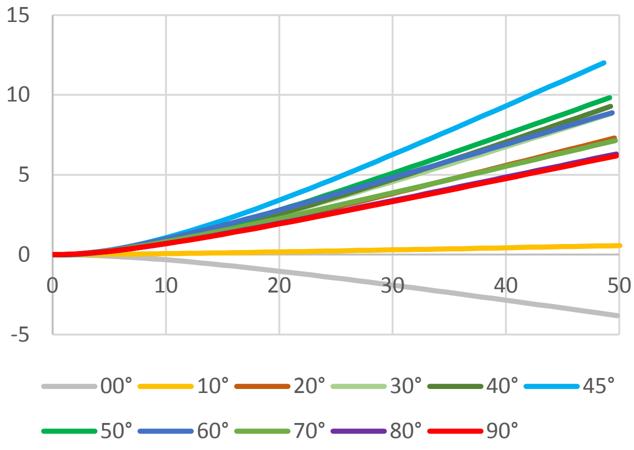

Figure 6. Deformation of GBC composite for various fibre orientations

Table 4. Impact of the GBC's orientation fibre on RF and Extension

Orientation	Extension (mm)	Reaction force (N)
0°	49.98611	75.09
10°	50.05269	29.45
20°	50.15165	133.4
30°	50.18638	118.1
40°	50.20359	83.32
45°	50.26107	86.98
50°	50.22008	65.19
60°	50.22141	70.45
70°	50.18456	57.66
80°	50.16246	47.06
90°	50.15838	48.65

Analysis of the GBC composite configuration under unidirectional force reveals several key insights. The 20° direction provides the highest reaction force (133.4 N) and moderate deformation, making it ideal for applications requiring strong resistance and moderate flexibility. The 30° orientation also performs well, with a high reaction force (118.1 N) and moderate deformation. Although the 10° direction has minimal distortion, it offers a significantly lower reaction force (29.45 N) compared to 20° and 30°. Higher angles, especially 90°, exhibit lower reaction forces (48.65 N) and higher deformation, indicating more elastic behaviour. Therefore, the 20° direction is optimal for applications that need a balance of minimal distortion with stronger feedback, while the 30° direction provides a robust alternative.

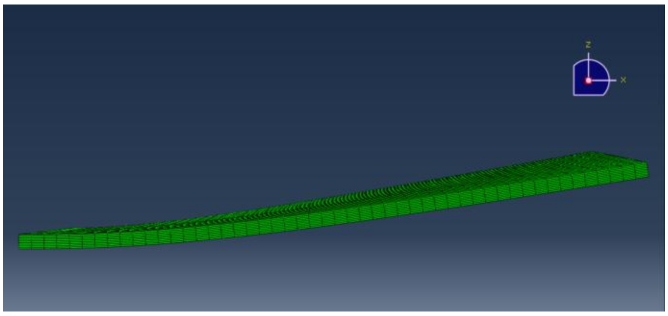

Figure 7. GBC displacement outcome at 20°

4. DISCUSSION

Analysis shows that all systems exhibit distinct mechanical behaviour at different angles, with the 0° and 20° orientation generally exhibiting higher productive capacities, indicating higher load-carrying capacity for applications requiring high strength and small deformation Because this direction is important. In contrast, a higher angle, such as 90°, always leads to a lower effective force and greater elongation, which means increased deformation and reduced stiffness, which means more elastic behaviour and highlights the trade-offs involved in fibre orientation choices

Other research shows that particular programs work better in certain aspects. For example, the performance of CGB at intermediate angles (e.g., 30°) is significantly improved compared to other configurations. This means that a downward slope can better balance strength and flexibility. The BCG design at 0° provides the best combination of high active strength and low deformation, making it ideal for applications requiring high strength and stiffness This design is particularly useful in situations where structural integrity and load-carrying capacity is very important. In addition, the GBC configuration at 20° provides high active strength in all configurations, which means good load distribution and stiffness, making it a strong choice for high-energy applications where power transmission is available even distribution of load and maintenance of stiffness is important.

Changing the hybrid composite composition to some angle can significantly influence the mechanical properties such as reaction force and deformation e.g., the GBC structure at 20°

outperforms the CGB and BCG structures at an angle, meaning fibre layers the sequence significantly affects performance. Similarly, the CGB model shows that even small changes in angle can lead to significant changes in mechanical behaviour. This sensitivity to angle changes emphasises the need for precise machining and careful consideration of fibre orientation in composites.

Also worth mentioning is the role of carbon/epoxy and boron/epoxy materials. Known for their high tensile strength, carbon/epoxy composites provide resistance to tensile forces and contribute to the overall durability of the composite mixture where this property is important where tensile strength is paramount. In contrast, boron/epoxy composites provide excellent compressive strength and toughness, ensuring that composites retain their structural integrity under load. Combining the tensile properties of carbon/epoxy with the stiffness of boron/epoxy results in a composite with well-balanced and durable performance profile the carbon/epoxy component helps to resist expansion or contraction of the mixture, while the boron/epoxy part adds stiffness, ensuring minimal deformation and shape under stress is maintained.

5. CONCLUSIONS

This study highlights the profound effect of fibre orientation on their mechanical behaviour under unidirectional forces and the process of incorporating boron epoxies into hybrid composites the study has revealed several key insights:

- Impact on Deformation: Composite structure, especially fibre sequence and orientation, is important in the deformation properties of hybrid composites the arrangement of different fibres such as carbon, glass, and boron affect how the mixture changes at the bottom greatly affected by the applied load. These design parameters affect the overall stiffness, flexibility, and load-carrying capacity of composite materials, with different fibre orientations causing variations in mechanical response with some configurations providing greater resistance to deformation, while others provide greater flexibility.

- Stronger in Tensile Strength: Carbon/epoxy composites, known for their excellent tensile strength, play an important role in the overall performance of hybrid composites the combination of carbon/epoxy in a hybrid structure enhances tensile properties, resulting in resistance against high tensile loads. This makes carbon/epoxy an important component of hybrid composites designed for applications where tensile strength is important. Notably, in tensile testing, bending in the direction of the carbon composite is observed in the CGB and GBC configurations.

- Stronger in Compressive Strength: Boron/epoxy is particularly known for its excellent compressive strength, making it valuable in hybrid composite systems and the additional cost without significantly increasing buckling tolerance the strength of the mixture does not increase. The strategic use of boron/epoxy improves the overall compressive performance, making the hybrid mixture suitable for applications where high compressive loads are expected, which is important for applications where material integrity is required under pressure.

- The combination of carbon/epoxy's high tensile strength and boron epoxy's stiffness creates a composite material with a balanced and robust performance profile. Carbon/epoxy composites are recognised for their ability to withstand pulling forces without significant deformation, making them ideal for applications requiring strength against tensile loads. In contrast, boron epoxy contributes stiffness, ensuring the composite retains its shape and structural integrity under load, which is crucial for applications demanding rigidity and minimal deformation. Together, these materials synergise to enhance the overall mechanical properties of the composite, providing a versatile solution that can meet the stringent requirements. This balanced performance profile makes carbon/epoxy and boron epoxy hybrid composites highly effective in applications where reliability, durability, and performance under diverse loading conditions are paramount.

- Effect of Fiber Orientation: The orientation of fibres in a composite has a significant effect on its mechanical properties. Fibers parallel to the applied force direction exhibit greater strength and stiffness, while those that are angularly oriented can improve force absorption and conversion Studies show that optimising fibre orientation can provide hybrid composite performance has improved significantly. Specific orientations can increase the tensile or compressive strength of a composite, making it more suitable for a particular application. Engineers can manipulate guided cables to achieve desired mechanical properties, such as increasing load carrying capacity or reducing deformation under tension.

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