NATURAL VS. SYNTHETIC FIBRES IN COMPOSITE LAMINATES: INFLUENCE OF HYBRIDIZATION ON LOW-VELOCITY IMPACT RESPONSE

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ABSTRACT

The increasing demand for lightweight and sustainable structural materials has driven significant attention toward hybrid composites that combine natural and synthetic fibres. While carbon fibre composites offer high stiffness and strength, they often fail in a brittle manner and have a large environmental footprint. In contrast, flax fibre composites provide greater energy absorption and sustainability benefits but suffer from lower stiffness and strength. Hybridization has been proposed as a promising strategy to merge the advantages of both types of fibres, yet the mechanisms governing their impact behaviour are still not fully understood. In this study, finite element simulations were conducted to evaluate the low-velocity impact response of carbon, flax, and carbon/flax hybrid laminates with different stacking sequences. The work focuses on identifying how fibre type and ply arrangement influence stiffness, toughness, and energy absorption, with the aim of establishing design guidelines for bio-hybrid composites. A central question addressed in this research is: *Can the hybridization of natural and synthetic fibres provide a balanced solution that meets the dual requirements of strength and sustainability in advanced composite structures?*

Keywords:

Bio-hybrid composites; Flax/carbon laminates; Low-velocity impact; Laminate symmetry; Energy absorption;

1 Introduction

1.1 Background

The increasing demand for lightweight and sustainable structural materials has driven significant interest in natural fibre reinforced polymers (NFRPs) as alternatives to fully synthetic fibre composites. Among natural fibres, flax has received particular attention due to its availability, relatively high specific strength, and environmental advantages. By contrast, carbon fibre reinforced polymers remain the benchmark for high-performance applications because of their exceptional stiffness and strength. However, the cost and environmental footprint of synthetic composites, combined with their limited energy dissipation under impact loading, have motivated the search for alternative or complementary solutions.

Natural fibre composites such as flax offer distinct advantages. They are derived from renewable resources and typically exhibit good damping and energy dissipation under dynamic loading. These qualities make them promising for applications where impact energy absorption and vibration control are critical. Nevertheless, their relatively low stiffness and strength compared to synthetic fibres limit their use in load-bearing structural components. On the other hand, synthetic composites such as carbon fibre provide superior mechanical resistance but generally absorb less impact energy, transmitting more of the load back to the structure or impactor. This trade-off between natural and synthetic fibres highlights the challenge of optimising composites for both strength and toughness.

One promising approach to addressing this challenge is hybridization, in which natural and synthetic fibres are combined within the same laminate. Such hybrids aim to leverage the stiffness and strength of synthetic fibres while integrating the toughness and energy absorption capability of natural fibres. The performance of hybrid laminates is strongly influenced by stacking sequence, ply orientation, and the placement of natural versus synthetic layers. For example, carbon skins may enhance bending stiffness, while flax layers in the core or outer surfaces can improve energy dissipation. Despite these advantages, the impact behaviour of hybrid laminates remains sensitive to laminate architecture, which complicates reliable design.

Although the literature on hybrid natural/synthetic composites is expanding, there remains a need for systematic numerical investigations that directly compare carbon, flax, and hybrid laminates under identical conditions. Numerical simulation provides a controlled platform to evaluate how material type and stacking sequence influence key responses such as reaction force, displacement, and stiffness during low-velocity impact. The present study addresses this need by modelling and analysing carbon, flax, and carbon/flax hybrid laminates with different configurations.

1.2 Objective

The aim of this study is to investigate the low-velocity impact (LVI) response of flax/epoxy, carbon/epoxy, and carbon/flax hybrid composite laminates using finite element simulation. Specifically, the objectives are to:

- Quantify and compare the global impact response of the laminate systems using consistent indicators, including reaction force, central deflection, stress response, and absorbed energy.
- Examine how stacking sequence, laminate symmetry, and outer-ply material (carbon-skin versus flax-skin) influence the stiffness–toughness trade-off under identical impact conditions.
- Synthesize the numerical outcomes into design-oriented guidelines for selecting sustainable bio-hybrid laminate architectures that balance stiffness retention, deformation capacity, and energy dissipation.

1.3 Literature Review

Research into hybrid composites that combine natural and synthetic fibres has gained momentum as industries seek sustainable yet high-performance materials. Early investigations such as **Audibert et al. (2017)** [1] reported the mechanical behaviour of Kevlar/flax/epoxy hybrid laminates, showing that hybridization can provide intermediate properties by combining the load-bearing capacity of synthetic fibres with the energy dissipation potential of natural fibres. These findings highlighted the relevance of bio-hybrid systems for applications requiring a balance between stiffness and toughness.

Building on this foundation, more recent work has integrated predictive and data-driven tools into composite research. **Masud et al. (2024)** [2] applied tree-based machine learning to predict the impact behaviour of carbon/flax bio-hybrid laminates, indicating that laminate architecture—particularly fibre distribution and stacking symmetry—can significantly influence predicted impact indicators. Similarly, **Masud et al. (2024)** [6] employed neural-network-based approaches to model low-velocity impact performance across hybrid configurations, showing that data-driven models can capture nonlinear relationships between laminate design variables and global response metrics.

Application-oriented studies have also expanded, particularly in biomedical and structural fields. **Kennedy et al. (2024)** [3] proposed carbon/flax bio epoxy hybrid bone-plate concepts aiming to improve biomechanical performance through tailored stiffness and controlled deformation. Likewise, **Sosiati et al. (2024)** [8] investigated abaca/carbon/epoxy hybrid composites for prosthetic socket applications, reporting that appropriate fibre combinations can balance strength-related requirements with functional comfort considerations.

In the context of engineering structures, numerical simulation has been widely used to explore stacking effects under impact loading. **Akram et al. (2024)** [4] simulated drop-weight impacts on natural/synthetic hybrid laminates using Abaqus, emphasizing that increasing the number of layers can enhance stiffness but may also lead to localized stress concentrations, which requires careful stacking design. In carbon/flax systems, **Masud and Mubashar (2024)** [5] investigated woven hybrid laminates and reported that sandwich-type configurations (e.g., carbon skins with flax core) can improve energy absorption and stabilise the impact response, highlighting the governing role of stacking order.

Economic considerations are also increasingly discussed in hybrid composite design. **Masud and Mubashar (2024)** [7] examined cost–performance trade-offs in carbon/flax bio-hybrid composites and suggested that partial flax substitution can substantially reduce cost while retaining a significant portion of mechanical performance, reinforcing hybridization as both a technical and economic strategy.

Hybridization strategies extend beyond fibre–fibre systems to fibre–metal laminates. **Zhang et al. (2025)** [9] studied impact resistance of fibre–metal hybrid composite laminates through experiments and simulations and reported improved specific energy absorption compared with conventional composite laminates, attributed to the complementary deformation mechanisms of ductile metallic layers and stiff composite plies. Finally, in a dynamic loading context, **Mabrouk et al. (2024)** [10] investigated the high strain-rate compressive behaviour of carbon–flax composites and reported pronounced strain-rate sensitivity, with hybrid laminates showing enhanced strength and more progressive response compared with fully natural-fibre systems.

Together, these studies demonstrate the breadth of research on hybrid composites—from predictive modelling and biomedical applications to structural optimisation and cost analysis. Overall, the common theme is that combining natural fibres such as flax with high-performance reinforcements (carbon, Kevlar, glass fibres, or metallic layers) enables laminate architectures with tuneable stiffness–toughness balance and application-specific impact performance [5,7,9].

Despite the progress reported in the literature, several gaps remain. First, many studies evaluate only a limited number of laminate configurations, which restricts systematic ranking of carbon, flax, and hybrid architectures under identical impact conditions and consistent performance indicators (Masud and Mubashar, 2024) [5]. Second, although stacking sequence is widely recognized as critical, the isolated effects of laminate symmetry and outer-ply selection (carbon-skin versus flax-skin concepts) are not consistently quantified within a unified comparative framework (Masud and Mubashar, 2024) [5,7]. Third, design-oriented conclusions are often not translated into concise laminate-selection rules, while numerical works may not always provide sufficient modelling detail or validation context to support reproducibility and direct comparison (Aransáez Ortega, 2019; Akram et al., 2024) [11,4].

Accordingly, the present study delivers a structured finite element comparison of carbon/epoxy, flax/epoxy, and carbon/flax bio-hybrid laminates subjected to identical low-velocity impact conditions. The analysis isolates the effects of laminate symmetry, outer-ply selection (carbon-skin versus flax-skin), and stacking strategy (interleaved versus symmetric) on key global response indicators, namely reaction force, central deflection, stress response, and absorbed energy. The resulting trends are consolidated into design-oriented recommendations to support sustainable laminate architecture selection.

2 Methodology

2.1 Materials and Geometry

The numerical study was carried out on square composite plates with dimensions of 500 × 500 mm and a total thickness of 3 mm. Each plate consisted of eight plies, with an individual ply thickness of 0.375 mm.

To evaluate the effect of fibre type, orientation, and stacking arrangement on the impact response, ten laminate configurations were designed. These configurations included pure carbon/epoxy laminates, pure flax/epoxy laminates, and carbon/flax hybrid laminates. The stacking sequences are summarized as follows:

Carbon/Epoxy Laminates

Carbon $[0]_8$: Unidirectional sequence, all fibres oriented at 0°.
Carbon $[0/90]_{2S}$: Symmetric cross-ply, sequence $[0/90/0/90]_S$.
Carbon $[0/90]_S$: Cross-ply with alternating 0° and 90° plies.

Flax/Epoxy Laminates

Flax $[0]_8$: Unidirectional sequence, all fibres oriented at 0°.
Flax $[0/90]_{2S}$: Symmetric cross-ply, sequence $[0/90/0/90]_S$.
Flax $[0/90]_S$: Cross-ply with alternating 0° and 90° plies.

Hybrid Laminates

Carbon/Flax (interleaved): Alternating carbon and flax plies [C/F/C/F/C/F/C/F], oriented at 0°/90°.
Flax/Carbon (interleaved): Alternating flax and carbon plies $[F/C/F/C/F/C/F/C]$, oriented at 0°/90°.
Flax/Carbon Symmetric Hybrid: Balanced layup $[F/C/F/C/C/F/C/F]$, arranged in symmetric cross-ply fashion.
Carbon/Flax Symmetric Hybrid: Balanced layup $[C/F/C/F/F/C/F/C]$, arranged in symmetric cross-ply fashion.

This set of configurations enabled a systematic comparison between unidirectional, cross-ply, and hybrid designs, allowing assessment of how material type and stacking sequence affect stiffness, energy absorption, and overall impact performance.

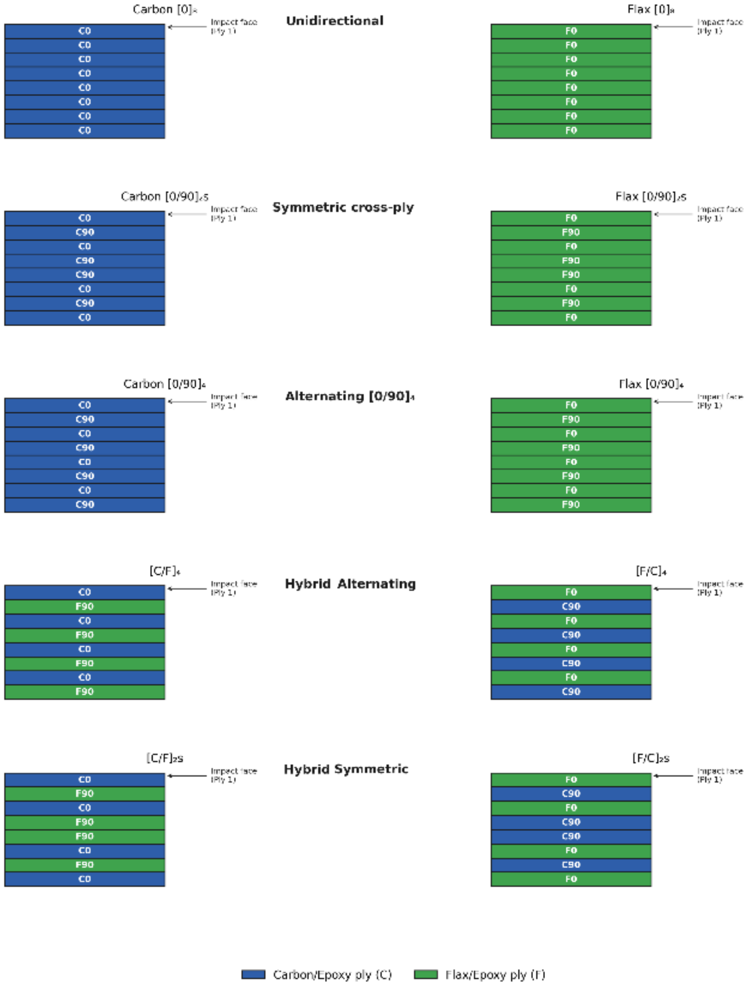

Fig. 1. Schematic representation of the investigated laminate configurations

2.2 Experimental Setup

The low-velocity impact was simulated using a rigid spherical impactor with a diameter of 70 mm and a mass of 5 kg. The sphere was positioned 50 mm above the centre of the laminate plate and released with an initial velocity of 5 m/s (5000 mm/s), corresponding to an impact energy of 62.5 J.

The composite plate measured 500 × 500 mm with a total thickness of 3 mm (eight plies of 0.375 mm each). All plate edges were fully clamped to eliminate rigid-body motion and to replicate fixed boundary conditions.

The finite element configuration of the simulation is shown in Figure 2, which illustrates the impactor and the clamped boundary conditions.

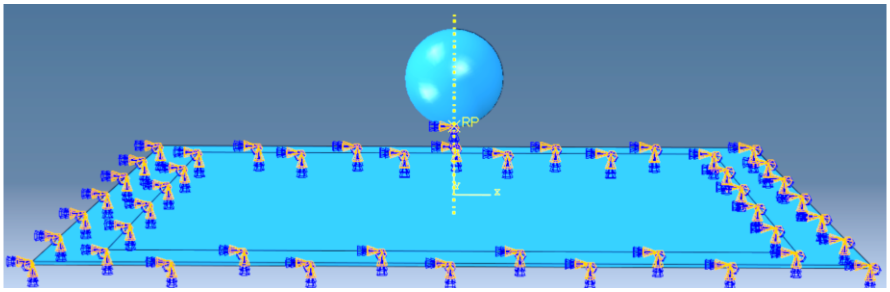

Fig. 2. Finite element model of the composite plate and spherical impactor with fully clamped boundary conditions

2.3 Model optimising Approach and Assumptions

The present study focuses on the global impact response of composite laminates under low-velocity impact loading. Simulations were performed using Abaqus/Explicit, which is well-suited for dynamic impact analysis due to its ability to handle complex contact interactions and large deformations. No explicit progressive damage model (e.g., Hashin failure criterion or cohesive zone modelling) was implemented in this study. Therefore, the analysis is limited to elastic behaviour and does not capture fibre breakage, matrix cracking, or delamination initiation and propagation.

2.4 Properties

Table 1. Properties of Flax/Epoxy, Carbon/Epoxy [12, 13]

Property	Carbon/Epoxy	Flax/Epoxy
Density	1520 kg/m^3	1250 kg/m^3
Young's Modulus (E)	E_x=135000 MPa	E_x=22980 MPa
	E_y=5331 MPa	E_y=3030 MPa
Poisson's Ratio (ν)	ν_{xy}=0.25	ν_{xy}=0.38
Shear Modulus (G)	G_{xy}=5411 MPa	G_{xy}=1040 MPa
	G_{yz}=2221 MPa	G_{yz}=1040 MPa
	G_{zx}=2221 MPa	G_{zx}=1060 MPa

2.5 Finite element discretization and contact

The laminate plate was discretized using SC8R continuum-shell elements (reduced integration) with a global mesh seed size of 10 mm. Contact between the rigid spherical impactor and the laminate was defined using a surface-to-surface contact formulation with hard normal contact and Coulomb friction ($\mu = 0.3$).

2.6 Method of Analysis

The evaluation of the laminate performance under low-velocity impact was based on the analysis of global response parameters obtained from the simulations. For each configuration, four indicators were extracted:

1. Peak reaction force (RF): the maximum load transmitted from the impactor to the plate during the event.
2. Maximum deflection (U): the highest out-of-plane displacement measured at the plate centre.
3. Stress (S): the maximum stress developed in the laminate during impact, extracted from field output.
4. Energy absorption (EA): the proportion of the initial impact energy dissipated by the laminate during loading.

$$E_A = \frac{1}{2}m{v_i}^2 - \frac{1}{2}m{v_f}^2$$

$$E_A(\%) = \frac{E_A}{E_I}$$

For clarity in interpretation, the laminates were grouped into three categories according to their fibre system and stacking sequence:

- Unidirectional laminates (UD): pure carbon $[0]_8$ and pure flax $[0]_8$.
- Cross-ply laminates: symmetric and non-symmetric sequences for both carbon and flax ($[0/90]_{2S}$, $[0/90]_4$).
- Hybrid laminates: carbon/flax combinations with interleaved or symmetric stacking sequences.

This comparative grouping enabled a structured evaluation of how fibre type (carbon, flax, or hybrid) and laminate design (UD, cross-ply, hybrid) affect the balance between strength, deformation behaviour, and energy dissipation.

3 Results

3.1 Unidirectional Laminates

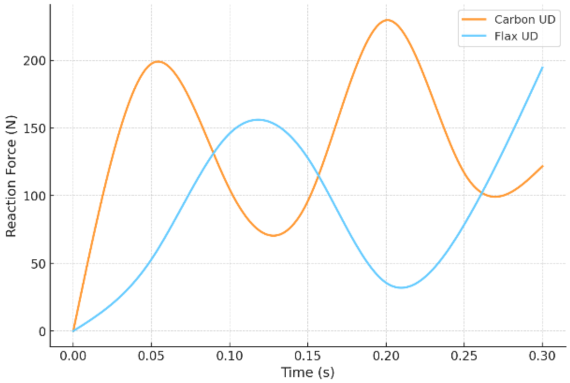

Fig. 3. Reaction force–time response of unidirectional laminates (Carbon/Epoxy $[0]_8$ vs Flax/Epoxy $[0]_8$)

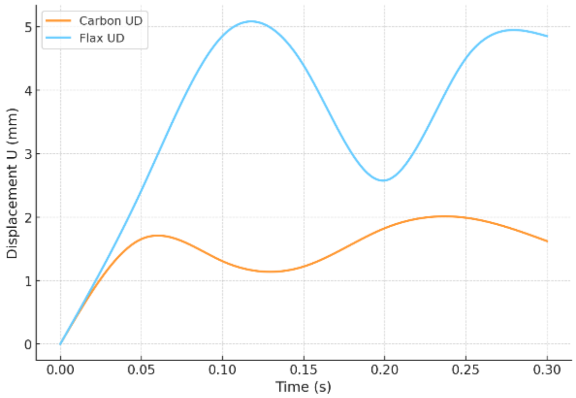

Fig. 4. Central deflection–time response of unidirectional laminates (Carbon/Epoxy $[0]_8$ vs Flax/Epoxy $[0]_8$)

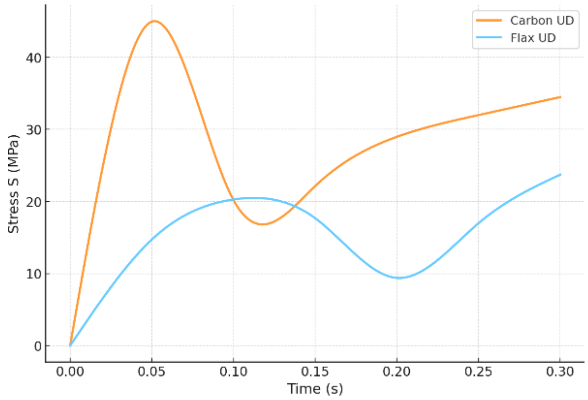

Fig. 5. Maximum stress–time response of unidirectional laminates (Carbon/Epoxy $[0]_8$ vs Flax/Epoxy $[0]_8$)

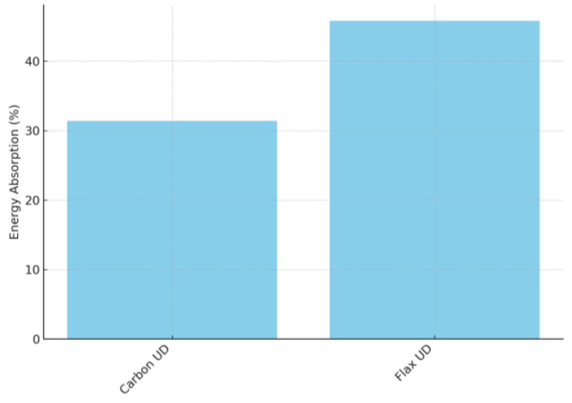

Fig. 6. Energy absorption–time response of unidirectional laminates (Carbon/Epoxy $[0]_8$ vs Flax/Epoxy $[0]_8$)

The unidirectional laminates exhibit distinct behaviours governed by fibre type. As shown in Fig. 3, the carbon $[0]_8$ laminate reaches a higher peak reaction force and transfers the load more rapidly (stiffer response), whereas the flax $[0]_8$ laminate shows a lower peak force but a longer contact duration, indicating a more compliant response. This trend is consistent with Fig. 4, where flax $[0]_8$ develops a larger central deflection than carbon $[0]_8$. The stress histories (Fig. 5) also reflect this contrast, with higher stress levels for carbon due to its reduced deformation. Importantly, Fig. 6 confirms that flax absorbs a larger fraction of the impact energy, while carbon prioritizes load-bearing capacity with lower energy dissipation.

3.2 Cross-Ply Laminates

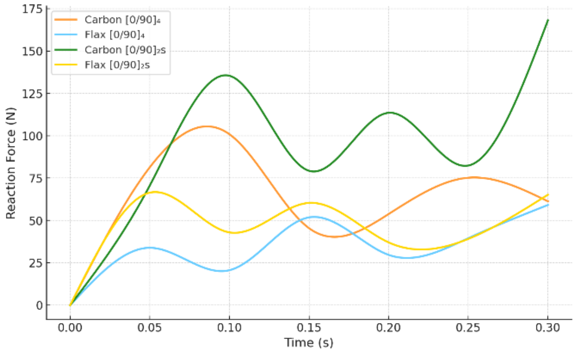

Fig. 7. Reaction force–time response of cross-ply laminates (carbon and flax configurations)

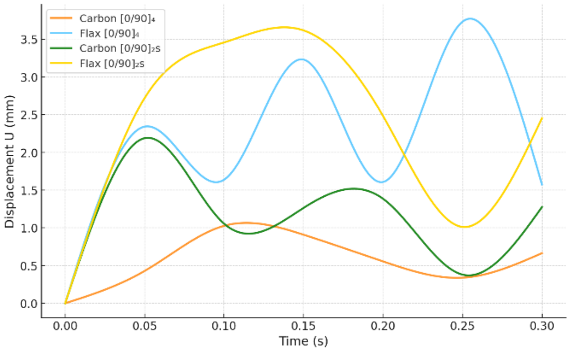

Fig. 8. Central deflection–time response of cross-ply laminates (carbon and flax configurations)

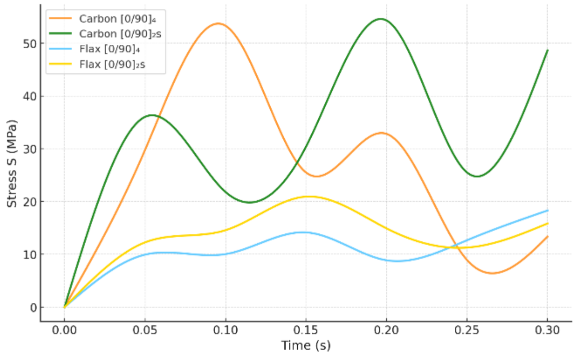

Fig. 9. Maximum stress–time response of cross-ply laminates (carbon and flax configurations)

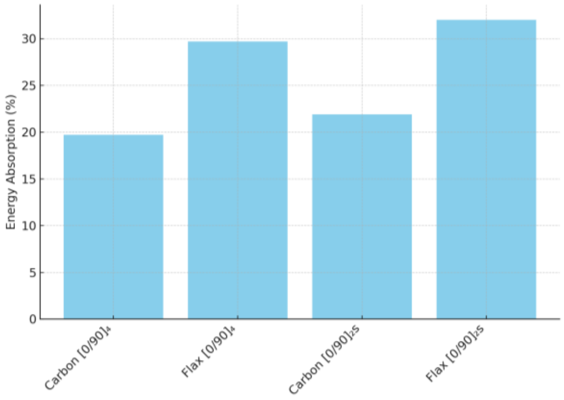

Fig. 10. Energy absorption–time response of cross-ply laminates (carbon and flax configurations)

Cross-ply laminates show more complex responses because 0° and 90° plies share the load. In Fig. 7, carbon cross-ply configurations exhibit higher reaction forces than flax cross-plies and show noticeable oscillations, which are associated with dynamic load redistribution between orthogonal plies. In contrast, flax cross-plies display lower force levels with a broader response, indicating prolonged contact and higher damping. The deflection curves (Fig. 8) confirm that flax cross-plies undergo larger central deflection than carbon cross-plies, while Fig. 9 shows higher stress levels for carbon systems. Finally, Fig. 10 indicates that cross-ply architecture enhances energy dissipation for flax more significantly than for carbon, emphasizing the sensitivity of natural-fibre laminates to stacking design.

3.3 Hybrid Laminates

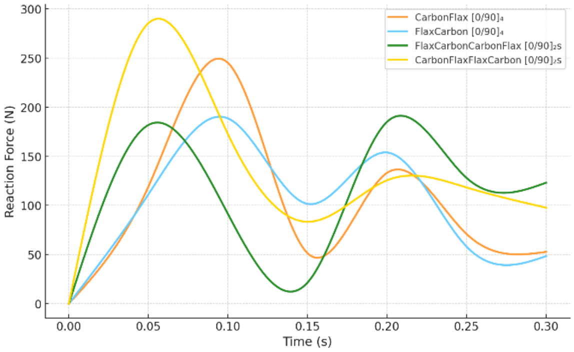

Fig. 11. Reaction force–time response of hybrid flax/carbon laminates

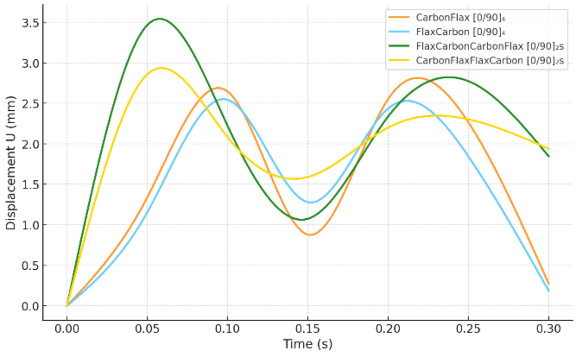

Fig. 12. Central deflection–time response of hybrid flax/carbon laminates

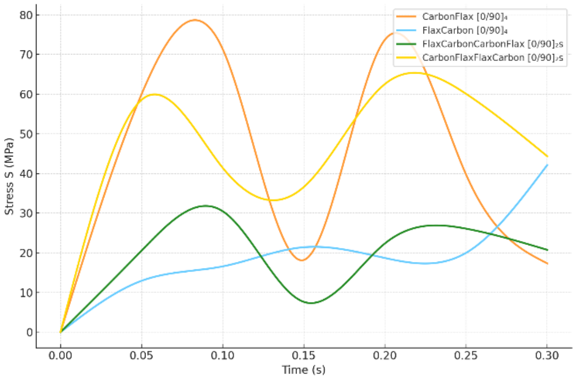

Fig. 13. Maximum stress–time response of hybrid flax/carbon laminates

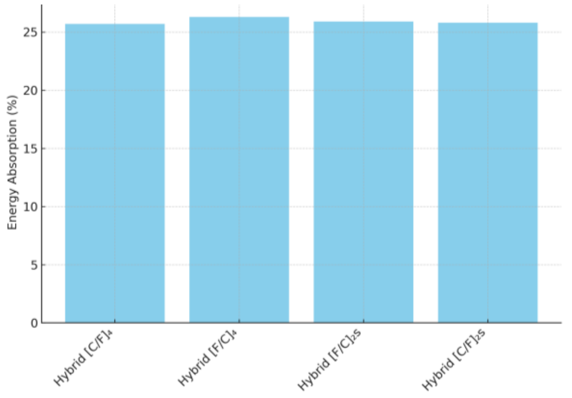

Fig. 14. Energy absorption–time response of hybrid flax/carbon laminates

Hybrid laminates exhibit intermediate behaviour that is strongly controlled by stacking sequence and outer-ply material. As shown in Fig. 11, hybrids with carbon outer plies develop higher peak forces (stiffness retention), whereas flax-skin hybrids show reduced peak forces and a longer response, indicating improved damping. The deflection histories (Fig. 12) confirm that flax-skin designs allow higher deformation, while carbon-skin designs restrict deflection. Stress results (Fig. 13) reflect this redistribution, with higher stress levels typically associated with carbon-dominated load paths. Importantly, Fig. 14 shows that hybrids absorb more energy than pure carbon laminates while maintaining higher load capacity than pure flax laminates, demonstrating a tuneable strength–toughness compromise through ply arrangement.

4 Discussion

The performance of composite laminates under impact is strongly influenced by fibre type, stacking sequence, and hybridization strategy. To provide meaningful insights, the results are examined through eight comparative groupings: unidirectional laminates, cross-ply laminates, alternative laminates, cross-ply versus alternative plies, hybrid alternative laminates, hybrid symmetric laminates, hybrid alternative versus hybrid symmetric laminates, and global energy absorption. Each grouping not only highlights the numerical differences observed but also explains the underlying mechanical reasons that govern the behaviour of the laminates.

4.1 Unidirectional Laminates (Carbon UD vs Flax UD)

Carbon UD:

The carbon UD laminate achieved a peak force of about 229.6 N with a maximum deflection of only 2.0 mm. The maximum stress was around 45 MPa, while energy absorption was limited to 31.4%. This behaviour reflects a stiffness and strength dominated response, but with lower energy dissipation.

Flax UD:

The flax UD laminate, in contrast, reached a slightly lower peak force of 194.6 N but allowed a much larger deflection of 4.9 mm. The maximum stress was approximately 23.7 MPa, significantly lower than carbon, but its energy absorption was much higher at 45.8%.

Key Difference:

Carbon UD shows higher peak force and lower deflection with lower absorbed energy, whereas flax UD shows larger deflection with higher absorbed energy.

4.2 Cross-Ply Laminates (Carbon $[0/90]_{2S}$ vs Flax $[0/90]_{2S}$)

Carbon $[0/90]_{2S}$:

This laminate recorded a peak force of about 168.1 N and a maximum deflection of 2.2 mm. The maximum stress was the highest among carbon systems, at 54.3 MPa, but its energy absorption remained low at 21.9%, confirming its stiffness-oriented behaviour.

Flax $[0/90]_{2S}$:

The flax cross-ply laminate achieved a lower peak force of 66.4 N, but its deflection was higher at 3.6 mm. The maximum stress was 20.9 MPa, and it absorbed 32% of the impact energy, showing improved stability compared to flax UD, although with lower absorbed energy than flax UD.

Key Difference:

Carbon cross-ply maintains higher peak force and higher stress with low absorbed energy, whereas flax cross-ply exhibits lower force but higher deflection and higher absorbed energy.

Mechanical reason:

Cross-ply symmetry improves load redistribution between 0° and 90° plies, but the intrinsic stiffness contrast remains dominant: carbon stays stiffness-driven, while flax benefits from compliance and enhanced dissipation pathways.

4.3 Alternative Laminates (Carbon $[0/90]_4$ vs Flax $[0/90]_4$)

Carbon $[0/90]_4$:

The alternative carbon laminate showed a peak force of 100.9 N, a maximum deflection of 1.0 mm, and stress of 32.8 MPa. Its energy absorption was only 19.7%, making it less effective than carbon cross-plies.

Flax $[0/90]_4$:

The flax alternative laminate reached a peak force of 59.1 N with a deflection of 3.7 mm. The maximum stress was lower at 18.3 Mpa, while energy absorption was 29.7%, slightly below that of flax cross-plies.

Key Difference:

Both materials show reduced impact efficiency in the non-symmetric alternating layup; flax remains more energy-absorbing than carbon but underperforms compared with symmetric flax cross-ply.

Mechanical reason:

Non-symmetric stacking reduces through-thickness balance and promotes less uniform stress transfer, lowering stability and energy dissipation efficiency relative to symmetric architectures.

4.4 Cross-Ply vs Alternative Ply (Carbon and Flax)

Cross-Ply Laminates:

The symmetric cross-ply architecture provides improved stability and more balanced load transfer during impact. In carbon laminates, this manifests as higher load resistance and higher stress levels with limited absorbed energy, whereas in flax laminates it promotes more stable deformation with comparatively improved energy dissipation.

Alternative Laminates:

The non-symmetric alternating sequences show reduced performance in both material systems. For carbon, the response is characterised by lower peak force, lower stress levels, and limited absorbed energy. For flax, absorbed energy remains moderate but still below that of symmetric flax cross-ply. The loss of symmetry tends to promote less predictable stress redistribution, which can reduce response stability compared with $[0/90]_{2S}$ designs.

Key Difference:

The symmetric cross-ply $[0/90]_{2S}$architecture provides a more stable and generally better-performing response than the non-symmetric alternating $[0/90]_4$ in both carbon and flax systems.

Mechanical reason:

Symmetry reduces bending–twisting coupling and improves stress redistribution through the thickness, leading to more predictable global response under impact.

4.5 Hybrid Alternative Laminates ($[C/F]_4$ vs $[F/C]_4$)

$[C/F]_4$:

The $[C/F]_4$ laminate achieved a peak force of 245 N and a deflection of 2.6 mm. The maximum stress was 73.8 MPa, much higher than pure flax laminates, while energy absorption was 25.7%.

$[F/C]_4$:

The $[F/C]_4$ laminate recorded a lower peak force of 188.5 N and a deflection of 2.5 mm. The maximum stress was reduced to 42.1 MPa, but energy absorption was slightly higher at 26.3%.

Key Difference:

$[C/F]_4$ increases peak force and stress compared with $[F/C]_4$, while absorbed energy remains close (≈25–26%).

Mechanical reason:

Carbon-dominant placement increases contact stiffness and load transfer capacity, whereas flax-forward placement increases compliance; non-symmetry introduces variability that limits large differences in global absorbed energy.

4.6 Hybrid Symmetric Laminates ($[C/F]_{2S}$ vs $[F/C]_{2S}$)

$[C/F]_{2S}$:

The $[C/F]_{2S}$ laminate achieved the highest peak force of all hybrids, at 285.4 N, with a deflection of 2.9 mm. The maximum stress was 62.6 MPa, and energy absorption was 25.8%.

$[F/C]_{2S}$:

The $[F/C]_{2S}$ laminate reached a lower peak force of 185 N with a deflection of 3.5 mm. The maximum stress was 30.5 MPa, but energy absorption was nearly identical at 25.9%.

Key Difference:

$[C/F]_{2S}$ maximises peak force (load capacity), while $[F/C]_{2S}$ increases compliance (higher deflection) with nearly identical absorbed energy.

Mechanical reason:

Outer plies control bending stiffness and contact stiffness (carbon skins stiffen, flax skins soften), while symmetry stabilises load redistribution, keeping global absorbed energy similar.

4.7 Hybrid Alternative vs Hybrid Symmetric Laminates

Hybrid Alternative ($[C/F]_4$ and $[F/C]_4$):

These laminates showed peak forces between 188 and 245 N, with deflections around 2.5–2.6 mm. The maximum stress varied widely from 42 to 74 MPa, and absorption was 25–26%. The absence of symmetry introduced variability.

Hybrid Symmetric ($[C/F]_{2S}$ and $[F/C]_{2S}$):

These laminates reached peak forces between 185 and 285 N, with deflections of 2.9–3.5 mm. The maximum stress ranged from 30 to 63 Mpa, and absorption was consistently 26%. The symmetric stacking improved stress distribution and stability.

Key Difference:

Symmetric hybrids provide a more balanced and reliable response with consistent energy absorption, whereas alternative (non-symmetric) hybrids can reach higher stress/force but show greater variability.

Mechanical reason:

Symmetry improves through-thickness balance and reduces coupling effects; non-symmetric layups can promote architecture-dependent stress localization and less predictable redistribution.

4.8 Global Energy Absorption (All Laminates)

Flax Laminates:

Absorbed between 30% and 46% of energy, with large deflections of 3.5–5 mm. The maximum stress was the lowest, between 18 and 24 MPa.

Carbon Laminates:

Absorbed only 19–22% of energy, with very small deflections of 1–2 mm. They showed high stress levels between 45 and 54 MPa.

Hybrid Laminates:

Absorbed consistently around 25–26% of energy, with moderate deflections of 2.5–3.5 mm, and a wider stress range, from 30 to 74 MPa, depending on stacking.

Key Difference:

Flax laminates absorb the most energy, carbon laminates absorb the least, and hybrids provide intermediate, tuneable performance.

Mechanical reason:

Global absorbed energy is primarily driven by deformation capacity and contact duration: compliant flax-rich laminates dissipate more energy via larger bending, stiff carbon-rich laminates limit deformation, and hybrids combine both mechanisms depending on ply placement and symmetry.

5 Conclusion

This study employed finite element simulations to examine the low-velocity impact response of carbon/epoxy, flax/epoxy, and carbon/flax bio-hybrid laminates with multiple stacking strategies under identical impact conditions. The comparative analysis confirms that the global impact behaviour is primarily controlled by fibre type and laminate architecture, with stacking sequence, laminate symmetry, and outer-ply placement acting as effective design parameters for tuning the stiffness–toughness balance. Across all configurations, carbon laminates exhibited a stiffness-dominated response characterised by higher load resistance and limited deformation, whereas flax laminates displayed greater compliance and higher global energy dissipation. Hybrid laminates consistently provided intermediate behaviour, indicating that partial flax substitution can deliver a meaningful compromise between stiffness retention and impact energy management.

The results highlight two key mechanisms. First, laminate symmetry improves response stability by promoting more balanced through-thickness stress redistribution and reducing coupling effects, which leads to more repeatable global indicators compared with non-symmetric alternating sequences. Second, outer-ply selection (carbon-skin versus flax-skin) strongly influences bending compliance and contact stiffness, thereby shifting the response toward higher peak force capacity (carbon-skin) or increased deformation capability (flax-skin), while maintaining comparable absorbed energy levels in symmetric hybrid designs. These observations support the concept that bio-hybrid laminate performance is not solely a function of constituent choice, but can be systematically tailored through stacking design.

Based on the present findings, the following design-oriented recommendations can be drawn for sustainable laminate selection under low-velocity impact loading:

- Stiffness/deflection-driven design: Carbon-dominant laminates are suitable when deflection limits and load resistance govern the design, as they provide higher contact stiffness and reduced global deformation.
- Energy-dissipation-driven design: Flax-rich laminates are preferred when impact energy absorption and reduced force transmission are prioritized, owing to their compliant response and higher global energy dissipation.
- Balanced sustainable solutions: Carbon/flax hybrids provide intermediate performance; carbon-skin hybrids are recommended when higher peak force capacity is required, whereas flax-skin hybrids are recommended when additional compliance is desired without substantially reducing global absorbed energy.
- Symmetry as a robust design rule: Symmetric stacking should be favoured over non-symmetric alternating sequences to improve impact response stability and reliability, particularly for hybrid architectures.

- Tuning via ply placement: The stiffness–toughness compromise can be adjusted by redistributing flax plies through the thickness and controlling the skin/core concept to meet application-specific targets.

Finally, it is noted that the present conclusions are derived from FE-based global response indicators. Future work should extend the study to multiple impact energy levels and incorporate experimental validation under identical configurations to enable one-to-one quantitative comparison and to further assess detailed failure mechanisms.

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