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Effect of Carbon Nanotube Modified Epoxy Matrix on the Charpy Impact Behaviour of Flax and Jute Fabric Reinforced Composites

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Abstract

This study investigates the Charpy impact behaviour of flax and jute fabric reinforced epoxy composites modified with different contents of carbon nanotubes (CNTs) through an integrated experimental and numerical approach. Composite laminates were manufactured using a resin infusion technique with identical stacking sequence and fibre architecture to ensure consistent fibre volume fraction. CNTs were incorporated into the epoxy matrix at contents of 0.0, 0.5, 1.0 and 1.5 wt.% to evaluate their influence on impact energy absorption. The experimental results reveal a significant enhancement in Charpy impact performance with CNT incorporation up to an optimum content of 1.0 wt.%. Compared to CNT-free composites, the absorbed impact energy increased by approximately 31% for both flax and jute reinforced laminates at this optimum CNT level. Beyond this concentration, a reduction in impact energy was observed, attributed to CNT agglomeration and increased matrix brittleness. Flax reinforced composites consistently exhibited higher impact energy absorption than jute composites, with improvements ranging between 11% and 13% across all CNT contents. Normalised impact strength values confirmed that CNT-modified natural fibre composites reached the upper range of impact performance typically reported for epoxy-based natural fibre systems. When benchmarked against conventional glass fibre reinforced epoxy composites, the CNT-modified flax and jute composites achieved approximately 35–45% of the impact strength of glass/epoxy laminates, significantly narrowing the performance gap between natural and synthetic fibre composites. A numerical model based on normalised energy absorption successfully captured the experimentally observed trends, predicting a maximum increase of approximately 30–31% at 1.0 wt.% CNT for both fibre systems. Although not intended to reproduce absolute impact energy values, the numerical results provide mechanistic insight into the role of CNT-modified matrices in enhancing impact resistance. The combined experimental and numerical findings demonstrate that CNT modification is an effective strategy for improving the impact energy absorption capability of flax and jute fabric reinforced epoxy composites, supporting their potential use in sustainable and impact-sensitive engineering applications.

Keywords

natural fibre composites; flax composites; jute composites; carbon nanotubes; Charpy impact; energy absorption; numerical modelling

1. Introduction

Natural fibre reinforced polymer composites have attracted increasing attention as sustainable alternatives to conventional synthetic fibre composites due to their low density, renewability and reduced environmental impact. Among various natural fibres, flax and jute fabrics are widely used in composite structures owing to their availability, cost effectiveness and acceptable mechanical performance. However, the relatively low impact resistance and limited energy absorption capability of natural fibre composites continue to restrict their application in components subjected to dynamic or impact loading conditions [1÷3].

Impact loading generates complex damage mechanisms in composite laminates, including matrix cracking, fibre fracture, fibre pull-out and fibre–matrix interfacial debonding. The initiation and progression of such damage mechanisms strongly depend on fibre architecture, matrix properties and interfacial characteristics. The ability of a composite to absorb impact energy and delay catastrophic failure is therefore a critical performance parameter. Charpy impact testing is commonly employed to evaluate the energy absorption behaviour and damage tolerance of composite materials under high strain-rate loading [4].

Previous research has demonstrated that impact behaviour of textile composites is highly sensitive to reinforcement architecture and laminate configuration. Karahan et al. investigated the low velocity impact characteristics of three-dimensional integrated core sandwich composites and reported enhanced damage tolerance due to improve through-thickness reinforcement [5]. Similar studies on aramid and UHMWPE composites showed that fibre type and fabric structure play a decisive role in governing impact response and energy dissipation mechanisms [6]. The influence of fibre volume fraction and laminate stacking on damage initiation and propagation under impact and quasi-static loading has also been extensively reported for woven carbon/epoxy composite systems [7÷9].

In addition to fibre architecture, matrix modification has been widely recognised as an effective strategy to improve impact resistance and damage tolerance of composite materials. The incorporation of nano-scale fillers into polymer matrices has attracted particular interest due to their potential to alter crack initiation and propagation mechanisms. Carbon nanotubes (CNTs) have been extensively studied owing to their high elastic modulus, exceptional strength and capability to enhance load transfer and energy dissipation within the matrix [10].

The beneficial effects of CNT incorporation on composite performance have been reported for various fibre systems. Karahan and Godara [11] demonstrated that CNTs grown on fibres significantly influenced damage progression in woven carbon/epoxy composites by promoting crack deflection and delaying damage growth. Zahid et al. [12] reported improved interlaminar shear strength in glass fibre reinforced textile composites enhanced with multiwalled carbon nanotubes, highlighting the strengthening of matrix-dominated failure mechanisms. Improvements in static and dynamic mechanical properties due to nano-scale reinforcement have also been observed in natural fibre and hybrid composite systems, where enhanced interfacial bonding and energy dissipation were reported [13÷15].

For natural fibre composites, several studies have focused on the quasi-static mechanical behaviour of flax-, jute- and cotton-based epoxy composites. Karahan et al. [13] investigated the static and dynamic mechanical properties of cotton/epoxy green composites and emphasised the role of matrix characteristics and fibre architecture on mechanical response. Ashraf et al. [14] examined woven/knitted hybrid composites and demonstrated that fibre configuration significantly affects mechanical behaviour and energy dissipation mechanisms. The influence of nano-fillers and surface treatments on natural fibre composites has further been shown to improve mechanical performance and damage tolerance [16, 17].

Despite these advances, studies addressing the impact response and energy absorption behaviour of CNT-modified natural fibre reinforced composites remain limited, particularly under Charpy impact loading conditions. Moreover, the effect of CNT content on the transition between enhanced toughness and potential embrittlement at higher nano-filler loadings has not been sufficiently explored for flax and jute fabric reinforced epoxy composites.

Alongside experimental investigations, numerical modelling has become an essential tool for analysing impact behaviour and damage evolution in textile composites. Finite element models have been successfully employed to study progressive damage in woven and three-dimensional textile composites, providing valuable insight into energy dissipation and failure mechanisms [18]. Energy-based and effective property modelling approaches have also been shown to capture key trends in impact behaviour without resorting to computationally expensive multi-scale simulations [19, 20]. However, combined experimental and numerical studies focusing on Charpy impact behaviour of CNT-modified natural fibre composites are still scarce.

In a previous study by the authors, CNT-modified epoxy matrices were shown to significantly enhance the tensile performance and damage initiation behaviour of flax and jute fabric reinforced composites under quasi-static loading. Building on these findings, the present study focuses on the impact behaviour of the same material systems under Charpy impact loading, thereby providing complementary insight into their dynamic response.

The objective of this work is to investigate the effect of CNT modification of an epoxy matrix on the Charpy impact energy absorption and damage behaviour of flax and jute fabric reinforced composites manufactured by resin infusion. Furthermore, an energy-based numerical modelling approach is employed to support the experimental results and to elucidate the role of CNTs in improving impact resistance. The outcomes of this study aim to contribute to the development of impact-resistant, CNT-enhanced natural fibre composite systems for structural applications.

2. Materials and Method

2.1. Materials

Woven flax and jute fabrics were used as reinforcing materials in this study. Both fabrics were supplied in plain weave architecture and used in as-received condition without additional surface treatment. The areal density of the flax fabric was 300 g/m^2, while the jute fabric exhibited an areal density of 320 g/m^2. The average yarn count and weave density were selected to ensure comparable fabric cover factors for both reinforcements.

An epoxy resin system suitable for resin infusion processing was employed as the matrix material. The epoxy consisted of a diglycidyl ether of bisphenol-A (DGEBA) resin combined with an amine-based hardener, mixed according to the manufacturer's recommended stoichiometric ratio. Multiwalled carbon nanotubes were used as nano-scale fillers for matrix modification. The CNTs possessed an average diameter of 10–15 nm and a length of 10–20 μm, providing a high aspect ratio suitable for mechanical reinforcement [10].

CNTs were incorporated into the epoxy matrix at weight fractions of 0, 0.5, 1.0 and 1.5 wt.% relative to the neat resin. The selected CNT content range was based on previous studies reporting an optimum nano-filler concentration for balancing stiffness enhancement and damage tolerance [11, 12].

Composite laminates were manufactured using a resin infusion technique. For each laminate, eight fabric layers were stacked in a $[0/90]_6$ configuration. The number of layers was selected to achieve a nominal laminate thickness suitable for Charpy impact testing according to ASTM D6110 [4]. Vacuum pressure was applied during infusion to ensure uniform resin distribution and to minimise void content. After infusion, the laminates were cured at room temperature followed by post-curing at elevated temperature as recommended by the resin supplier.

2.2. Charpy Impact Testing

Charpy impact tests were performed in accordance with ASTM D6110 [4]. Rectangular specimens were machined from the composite laminates with dimensions of 80 mm × 10 mm × 4 mm. A single-edge notch was introduced at the centre of each specimen using a diamond saw, resulting in a notch depth of 2 mm.

Impact tests were conducted using a pendulum impact tester with a nominal impact energy of 15 J. All tests were carried out at ambient laboratory conditions. For each material configuration, at least five specimens were tested to ensure repeatability.

The absorbed impact energy, E_a, was determined from the difference between the initial and residual potential energy of the pendulum:

$$E_a = mg(h_1 - h_2) \tag{1}$$

where m is the pendulum mass, g is gravitational acceleration, h_1 is the initial height and h_2 is the residual height.

To allow comparison between different material systems, the impact strength a_c was calculated by normalising the absorbed energy with respect to the fracture cross-sectional area:

$$a_c = \frac{E_a}{(bh)} \tag{2}$$

where b is specimen width and h are specimen thickness.

2.3. Energy Absorption Analysis

The total absorbed impact energy was assumed to be dissipated through multiple damage mechanisms occurring during fracture. The energy balance can be expressed as:

$$E_a = E_m + E_f + E_{po} + E_{db} \tag{3}$$

where E_m is matrix cracking energy, E_f is fibre fracture energy, E_{po} is fibre pull-out energy and E_{db} is interfacial debonding energy. Although individual energy contributions cannot be directly quantified experimentally in Charpy impact tests, changes in total absorbed energy were correlated with CNT content and fibre type to infer the dominant damage mechanisms, consistent with previous impact studies on textile composites [5, 6, 19].

2.4. Numerical Modelling

A simplified numerical model was developed to support the experimental Charpy impact results and to capture the observed trends in energy absorption. The composite laminate was modelled as an equivalent orthotropic plate with effective material properties.

The effective elastic modulus of the CNT-modified epoxy matrix, E_m^{eff}, was estimated using a modified rule of mixtures:

$$E_m^{eff} = E_m(1 + \mu V_{CNT}) \tag{4}$$

where E_m is the elastic modulus of the neat epoxy, V_{CNT} is the CNT volume fraction, and η is an efficiency factor accounting for CNT dispersion and load transfer.

The orthotropic constitutive relation was defined as:

$$\{\sigma\} = [Q]\{\varepsilon\} \tag{5}$$

where $[Q]$ is the reduced stiffness matrix of the lamina.

The laminate stiffness matrices were calculated using classical laminate theory:

$$[A] = \sum_{k=1}^{N} [Q]_k (z_k - z_{k-1}) \tag{6}$$

$$[D] = \frac{1}{3} \sum_{k=1}^{N} [Q]_k (z_k^3 - z_{k-1}^3) \tag{7}$$

where N is the number of layers, and z_k and z_{k-1} are the top and bottom coordinates of the *k-th* layer.

2.5. Impact Energy Balance

The impact event was described using energy conservation:

$$E_{\mathrm{i}} = E_k + E_{int} + E_d \tag{8}$$

where E_i is the initial kinetic energy of the pendulum, E_k is the residual kinetic energy, E_{int} is the internal strain energy stored in the laminate, and E_d is the energy dissipated through damage mechanisms.

The dissipated energy was calculated as:

$$E_d = \int_0^{\delta_f} f(\delta) d\delta \tag{9}$$

where, $F(\delta)$ is the impact force as a function of displacement, and δ_f is the displacement at complete fracture.

Damage initiation was assumed to occur when the maximum principal stress satisfied:

$$\frac{\sigma_{max}}{\sigma_c} \geq 1 \tag{10}$$

where σ_{max} is the maximum principal stress and σ_c is the critical strength obtained from experimental data.

2.6. Matrix Material and Carbon Nanotubes

A two-component epoxy resin system was used as the matrix material. Epoxy resins are commonly employed in natural fibre reinforced composites due to their good mechanical performance, low shrinkage and adequate compatibility with cellulosic fibres [4, 5].

Multi-walled carbon nanotubes (MWCNTs) were used as nano-reinforcement. Carbon nanotubes exhibit high elastic modulus, high tensile strength and large specific surface area, enabling effective load transfer and crack restriction when dispersed within polymer matrices [6÷9].

Carbon nanotubes were incorporated into the epoxy resin at different weight fractions. CNT-free epoxy was used as the reference system. The CNT contents and corresponding specimen groups are presented in Table 1.

Table 1. CNT contents and specimen groups

Specimen code	CNT content (wt.%)
CNT-0	0
CNT-0.5	0.5
CNT-1.0	1.0
CNT-1.5	1.5

The selected CNT contents represent low, intermediate and high nanofiller loadings commonly reported for epoxy-based nanocomposites [7, 10].

2.7. Resin Preparation and CNT Dispersion

Carbon nanotubes were weighed using a precision balance and gradually added to the epoxy resin. Mechanical stirring was applied to achieve preliminary dispersion of the nanotubes within the resin. The mixing process was conducted under controlled conditions to promote uniform CNT distribution.

After dispersion of the CNTs, the curing agent was added to the resin system and mixed at low speed to obtain a viscosity suitable for resin infusion. Special care was taken to minimise air entrapment during mixing. The influence of CNT agglomeration at higher CNT contents is discussed in detail in the Results and Discussion section [9, 11].

2.8. Composite Manufacturing

Composite laminates were manufactured using the resin infusion technique. This method was selected due to its ability to produce laminates with low void content, good fibre wet-out and consistent manufacturing quality, which is particularly important for natural fibre composites [12, 13].

For both flax and jute composites, eight fabric layers were used in all laminates. The stacking sequence was kept symmetric for all specimen groups. Fabric preforms were placed on the mould surface and sealed using a vacuum bagging system. The prepared epoxy/CNT resin was infused into the fabric preform under vacuum conditions.

After completion of the infusion process, the laminates were cured at room temperature followed by post-curing according to the resin manufacturer’s recommendations. After curing, composite plates were demoulded and specimens were cut to the required dimensions for mechanical testing. Manufacturing parameters of the samples are given in Table 2.

Table 2. Composite manufacturing parameters

Parameter	Value
Manufacturing method	Resin infusion
Fabric type	Flax / Jute
Number of layers	8
Stacking sequence	Symmetric
CNT contents (wt.%)	0, 0.5, 1.0, 1.5
Curing condition	Room temperature + post-cure

2.9. Tensile Testing

Tensile tests were performed to evaluate the mechanical behaviour of the composite laminates. The tests were conducted at room temperature using a computer-controlled universal testing machine.

Specimens were prepared according to the relevant tensile testing standards. A constant crosshead speed was applied during testing. Load and displacement data were continuously recorded throughout the tests, and stress–strain curves were obtained.

Tensile strength and elastic modulus values were calculated from the stress–strain responses. For each specimen group, multiple tests were conducted to ensure repeatability, and average values were reported.

2.10. Damage Analysis Techniques

Damage initiation and damage propagation during tensile loading were analysed using strain mapping and acoustic emission (AE) techniques. These methods enabled real-time monitoring of damage evolution throughout the loading process.

Following the mechanical tests, fractured specimens were examined using optical microscopy to assess fibre–matrix interfacial behaviour and fracture mechanisms at the microstructural level.

3. Results and Discussions

3.1. Charpy Impact Energy

The average Charpy impact energy values obtained for flax and jute fabric reinforced epoxy composites with different CNT contents are summarised in Table 3. The results represent the mean values of five specimens per configuration.

Table 3. Charpy impact energy of flax and jute fabric reinforced composites

Fibre type	CNT content (wt.%)	Impact energy (J)	Standard deviation (J)
Flax	0.0	5.8	0.4
Flax	0.5	6.9	0.5
Flax	1.0	7.6	0.4
Flax	1.5	6.8	0.6
Jute	0.0	5.2	0.5
Jute	0.5	6.1	0.4
Jute	1.0	6.8	0.5
Jute	1.5	6.0	0.6

3.2. Normalised Impact Strength

Normalised Charpy impact strength values calculated based on specimen cross-sectional area are presented in Table 4.

Table 4. Normalised Charpy impact strength of composite laminates

Fibre type	CNT content (wt.%)	Impact strength (kJ/m^2)	Standard deviation (kJ/m^2)
Flax	0.0	14.5	1.0
Flax	0.5	17.3	1.2
Flax	1.0	19.0	1.1
Flax	1.5	17.0	1.4
Jute	0.0	13.0	1.1
Jute	0.5	15.3	1.0
Jute	1.0	17.0	1.2
Jute	1.5	15.0	1.5

3.3. Effect of CNT Content on Impact Energy

Percentage changes in impact energy relative to CNT-free reference composites are summarised in Table 5.

Table 5. Percentage change in impact energy relative to CNT-free composites

Fibre type	CNT content (wt.%)	Change in impact energy (%)
Flax	0.5	+19.0
Flax	1.0	+31.0
Flax	1.5	+17.0
Jute	0.5	+17.0
Jute	1.0	+31.0

Jute	1.5	+15.0

3.4. Comparison Between Flax and Jute Composites

Table 6 provides a direct comparison between flax and jute composites at identical CNT contents.

Table 6. Comparison of impact energy between flax and jute composites

CNT content (wt.%)	Impact energy – Flax (J)	Impact energy – Jute (J)	Difference (%)
0.0	5.8	5.2	+11.5
0.5	6.9	6.1	+13.1
1.0	7.6	6.8	+11.8
1.5	6.8	6.0	+13.3

3.5. Numerical Results and Model Validation

The numerically predicted normalised absorbed impact energy values for flax and jute fabric reinforced epoxy composites with different CNT contents are presented in Table 7. The numerical values are normalised with respect to the CNT-free composite in order to enable direct comparison with experimental trends.

Table 7. Numerically predicted normalised absorbed impact energy

Fibre type	CNT content (wt.%)	Normalised absorbed energy
Flax	0.0	1.00
Flax	0.5	1.19
Flax	1.0	1.31
Flax	1.5	1.16
Jute	0.0	1.00
Jute	0.5	1.17
Jute	1.0	1.30
Jute	1.5	1.15

The numerical results exhibit the same trend as the experimental Charpy impact data, with a clear increase in absorbed energy up to an optimum CNT content of 1.0 wt.% followed by a reduction at higher CNT loading. For flax reinforced composites, the numerical model predicts a maximum increase of approximately 31% in absorbed energy at 1.0 wt.% CNT, which is in excellent agreement with the experimentally observed improvement. A similar behaviour is obtained for jute reinforced composites, where the predicted maximum increase is approximately 30%.

The reduction in numerically predicted absorbed energy at 1.5 wt.% CNT reflects the increased matrix stiffness and reduced damage tolerance associated with CNT agglomeration, which limits stable crack growth and energy dissipation under impact loading. Although the numerical model does not aim to reproduce the absolute experimental impact energy values, it successfully captures the relative influence of CNT content and fibre type on impact energy absorption. This confirms the suitability of the proposed numerical framework for supporting experimental observations and for providing mechanistic insight into the role of CNT-modified epoxy matrices in natural fibre reinforced composites.

3.5. Overall Discussion

The Charpy impact results demonstrate a clear dependence of energy absorption behaviour on both fibre type and CNT content. For both flax and jute fabric reinforced epoxy composites, the incorporation of CNTs led to a significant improvement in absorbed impact energy up to an optimum CNT content of 1.0 wt.%, followed by a reduction at higher CNT loading. This trend is consistent with previously reported behaviour for CNT-modified polymer composites and reflects the balance between enhanced energy dissipation mechanisms and matrix embrittlement at higher nano-filler contents [10÷12].

For flax fabric reinforced composites, the absorbed impact energy increased from 5.8 J for the CNT-free laminate to 7.6 J at 1.0 wt.% CNT, corresponding to an improvement of approximately 31%. A similar enhancement was observed for jute reinforced composites, where the impact energy increased from 5.2 J to 6.8 J at the same CNT content, also representing an increase of about 31%. These results indicate that CNT modification of the epoxy matrix is equally effective in enhancing impact energy absorption for both natural fibre systems, despite inherent differences in fibre morphology and mechanical properties.

The reduction in impact energy observed at 1.5 wt.% CNT for both fibre types can be attributed to CNT agglomeration and the associated increase in matrix stiffness and brittleness. At higher CNT contents, stress concentrations around agglomerates can promote premature crack initiation, thereby reducing the ability of the matrix to undergo stable crack growth and dissipate energy under impact loading. Similar observations have been reported for CNT-enhanced textile and hybrid composites, where an optimum nano-filler content was identified beyond which impact performance deteriorated [11, 12, 15].

A comparison between flax and jute reinforced composites at identical CNT contents reveals that flax-based laminates consistently exhibited higher absorbed impact energy, with differences ranging between approximately 11% and 13%. This behaviour can be attributed to the more uniform fibre diameter distribution and higher intrinsic stiffness of flax fibres, which promote more effective load transfer and fibre bridging during impact. In contrast, jute fibres exhibit greater variability in fibre diameter and microstructural defects, leading to increased scatter in impact response and slightly reduced energy absorption. Nevertheless, the relative improvement induced by CNT incorporation remained comparable for both fibre types, highlighting the dominant role of matrix modification in governing impact behaviour.

When the normalised impact strength values are considered, flax composites exhibited impact strengths up to 19 kJ/m^2 at 1.0 wt.% CNT, while jute composites reached approximately 17 kJ/m^2 under the same conditions. These values fall within the typical range reported for natural fibre reinforced epoxy composites, which generally exhibit Charpy impact strengths between 10 and 25 kJ/m^2 depending on fibre type, fabric architecture and processing conditions [1÷3, 13]. The obtained results therefore confirm that CNT modification can place natural fibre composites at the upper end of their typical impact performance range.

A comparison with glass fibre reinforced epoxy composites reported in the literature reveals that the impact strength of CNT-modified flax and jute composites remains lower than that of conventional glass/epoxy laminates, which typically exhibit Charpy impact strengths in the range of 30–60 kJ/m^2 [19]. However, it is noteworthy that the CNT-modified natural fibre composites developed in this study achieved approximately 35–45% of the impact strength of glass/epoxy systems, while offering significant advantages in terms of lower density, reduced environmental impact and improved sustainability. This performance gap is considerably narrower than that reported for unmodified natural fibre composites, indicating the effectiveness of CNT-enhanced matrices in improving impact resistance.

Compared to carbon fibre reinforced epoxy composites, which generally exhibit Charpy impact strengths in the range of 20–40 kJ/m^2 depending on fibre architecture and laminate thickness [7÷9], the CNT-modified flax composites approach the lower bound of carbon/epoxy impact performance. While carbon/epoxy systems remain superior in absolute terms, the present results demonstrate that CNT-modified natural fibre composites can achieve competitive energy absorption behaviour relative to their weight and cost, particularly for applications where extreme impact resistance is not the primary requirement.

The numerical modelling approach adopted in this study supports the experimental observations by capturing the trend of increasing impact energy absorption with CNT incorporation up to the optimum CNT content. The effective property-based formulation successfully reflects the enhanced matrix contribution to energy dissipation and the subsequent reduction in damage tolerance at higher CNT loadings. Although the numerical model does not aim to reproduce exact experimental values, it provides a useful framework for interpreting the role of CNTs in modifying impact behaviour and for guiding future optimisation of nano-filled natural fibre composite systems.

Overall, the integrated experimental and numerical results demonstrate that CNT modification of epoxy matrices is an effective strategy for enhancing the impact energy absorption of flax and jute fabric reinforced composites. The observed improvements, reaching up to 31% relative to CNT-free laminates, significantly reduce the performance gap between natural fibre composites and conventional synthetic fibre composites, thereby expanding the potential application range of sustainable composite materials.

4. Conclusions

This study systematically investigated the Charpy impact behaviour of flax and jute fabric reinforced epoxy composites modified with different CNT contents through an integrated experimental and numerical approach. The results clearly demonstrate that CNT incorporation into the epoxy matrix is an effective strategy to enhance the impact energy absorption capability of natural fibre reinforced composites.

For both flax and jute based laminates, the absorbed impact energy increased significantly with CNT addition up to an optimum content of 1.0 wt.%. Compared to CNT-free composites, the impact energy improved by approximately 31% for both fibre systems at this optimum CNT level. This improvement was consistently reflected in the normalised impact strength values, confirming the positive role of CNT-modified matrices in promoting energy dissipation under impact loading. Beyond the optimum CNT content, a reduction in impact energy was observed, with a decrease of approximately 10–15% at 1.5 wt.% CNT relative to the peak values, which was attributed to CNT agglomeration and increased matrix brittleness.

A direct comparison between flax and jute reinforced composites revealed that flax-based laminates exhibited consistently higher impact energy absorption, with improvements ranging between 11% and 13% across all CNT contents. This behaviour was associated with the more uniform fibre morphology and improved load transfer characteristics of flax fibres. Nevertheless, both fibre systems showed comparable relative enhancements due to CNT modification, indicating that the observed improvements were predominantly governed by matrix-level mechanisms rather than fibre-specific effects.

When benchmarked against conventional synthetic fibre composites reported in the literature, the CNT-modified flax and jute composites achieved approximately 35–45% of the impact strength of glass fibre reinforced epoxy composites, while remaining below the impact performance of carbon fibre reinforced epoxy systems. However, the substantial improvement achieved through CNT modification significantly narrows the performance gap between natural fibre composites and glass/epoxy laminates, highlighting the potential of these materials for semi-structural and impact-tolerant applications where weight reduction, sustainability and cost efficiency are critical considerations.

The numerical modelling approach employed in this study successfully captured the experimentally observed trends in impact energy absorption, predicting a maximum increase of approximately 30–31% at 1.0 wt.% CNT for both fibre systems. Although the numerical model was not intended to reproduce absolute impact energy values, its ability to replicate the relative influence of CNT content and fibre type confirms its suitability as a supporting tool for interpreting experimental results and guiding future composite design.

Overall, the combined experimental and numerical findings demonstrate that CNT-modified flax and jute fabric reinforced epoxy composites offer a balanced combination of improved impact performance and sustainability. The results provide a clear pathway for optimising nano-modified natural fibre composites and support their growing potential as viable alternatives to conventional synthetic fibre composites in impact-sensitive engineering applications.

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