



Tensile and Low Velocity Impact Behaviour of Flax Fiber Reinforced Composite Modified with Multi-Walled Carbon Nanotubes

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ABSTRACT

The utilization of natural fibers as sustainable materials in composites has gained significant attention in recent years. This study investigates the tensile and low-velocity impact behavior of flax fiber-reinforced composites modified with multi-walled carbon nanotubes (MWCNTs). The primary objective is to evaluate the mechanical performance enhancements achieved by incorporating MWCNTs into woven flax fibers through a vacuum bagging process. Flax fiber with varying MWCNT concentrations (0-3 wt.%) were fabricated and subjected to tensile and drop-weight impact tests. The tensile test results revealed that the incorporation of MWCNTs significantly improved the tensile strength of the composites, with the FF/PE-CNT3 sample exhibiting a 6.23% increase compared to the control sample (FF/PE). Scanning Electron Microscopy (SEM) analysis demonstrated better dispersion and interaction of MWCNTs within the composite matrix, leading to enhanced load transfer and mechanical properties. Impact tests showed a marked increase in energy absorption with higher MWCNT content. The FF/PE-CNT3 sample absorbed 43.81 J at 30 J impact energy, indicating a 31.81% improvement over the control sample. The enhanced energy absorption is attributed to the excellent interfacial bonding and effective load distribution facilitated by the MWCNTs. These findings suggest that MWCNT-modified flax fiber composites exhibit superior mechanical properties, making them promising candidates for applications requiring high strength and impact resistance. The study contributes to the development of advanced natural fiber-reinforced composites with improved performance for sustainable engineering applications.

1. Introduction

Natural fibers have long been used as fillers for thermosets [1]. However, with the increasing demand for sustainable materials, they are now being incorporated into thermoplastics as high-performance additives [2]. The focus on sustainability has spurred significant interest in natural fiber-reinforced polymer composites (NFRPCs), expanding their application beyond the automotive and construction industries into various other fields [3]. There remain numerous opportunities for further exploration of their potential, particularly in high-level structural applications, such as primary

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components in bulletproof or ballistic materials. The advantageous properties of these fibers, including low cost, lightweight nature, and biodegradability, make them an attractive alternative to synthetic fibers [4]. As research in this area continues to grow, it is anticipated that more innovative uses for natural fibers will be discovered across various fields, leading to greater adoption of sustainable practices.

Among the various plant fibers studied, flax fiber has emerged as a highly viable material for composite applications, garnering significant recognition for its mechanical properties. Chemically, flax fibers are composed of approximately 71% cellulose and 19.6% hemicellulose, with smaller amounts of pectin (2.2%), lignin (2.2%), and wax (1.5%) [5]. The primary constituent, cellulose, contains abundant hydroxyl groups, which contribute to the inherent incompatibility between the hydrophilic fibers and the hydrophobic matrix [6]. This incompatibility often leads to weak interfacial bonding and subsequently lower mechanical properties [7]. To address these challenges, extensive research has focused on enhancing the physical and chemical characteristics of flax fibers through various treatments, such as enzyme retting and alkali treatment [8]. These modifications aim to improve the strength-to-weight ratio and durability of the fibers while minimizing their environmental impact. Additionally, researchers have explored hybridization strategies, combining natural fibers like flax with synthetic counterparts to develop advanced composites for a wide range of industries, including aerospace and automotive engineering [9,10].

In recent years, carbon nanotubes have shown great potential for the construction of multi-dimensional fiber-reinforced composites, offering enhanced interfacial and mechanical properties [11]. A study by Hashim *et al.*, [12] demonstrated that the yield strength, ultimate tensile strength, and elongation to fracture of an alloy composite with multi-walled carbon nanotubes (MWCNTs) were 316 MPa, 347 MPa, and 13.3%, respectively, which were significantly superior to those of dual-reinforced composites. Shen *et al.*, [13] found that the addition of MWCNTs improved the mechanical and fracture properties of ramie fiber-reinforced composites. The mechanical properties of the ramie fiber were enhanced due to an increased extent of reaction between the matrix and fiber, facilitated by the catalytic effect of the CNTs. The mechanisms typically involve mechanical interlocking between the CNTs and the matrix, leading to a greater surface area and improved fiber wettability. Additionally, this interaction strengthens the matrix adjacent to the interface region [14].

However, the synthetic nature of some fibers often results in their surfaces being relatively unresponsive to robust chemical interactions with carbon nanotubes. In contrast, the numerous hydroxyl groups present on flax fibers have the potential to form chemical bonds with the functional groups on carbon nanotubes (CNTs), thereby enhancing the interaction between these fibers and CNTs. According to Hu *et al.*, [15], when acid-coated single-wall carbon nanotubes come into contact with cotton sheets, a notable attractive force is observed. This attraction results from significant van der Waals forces and hydrogen bonding, which facilitate strong bonding between the two materials. Unlike synthetic fibers, natural plant fibers possess functional groups that can effectively incorporate CNTs, thereby altering the interfacial characteristics of the composites. This is attributed to the distinct functional groups on CNTs, which can interact with those present in plant fibers, offering a viable approach for enhancing composite materials [15].

The aim of this research is to investigate the incorporation of MWCNTs into woven flax fibers through a vacuum bagging process. The primary objective is to examine and analyze how CNTs, as reinforcing agents, influence the mechanical properties of MWCNT-flax fiber composites. To achieve this, the study thoroughly evaluates the tensile strength and impact resistance of the composites, aiming to explore the potential for further hybridization between nanomaterials and natural fibers. By conducting tensile and drop-weight impact tests, the research seeks to provide a comprehensive understanding of the mechanical behavior of these composites. The incorporation of MWCNTs is

expected to enhance the interaction between the flax fibers and the polymer matrix, leading to improved load transfer and mechanical performance.

2. Methodology

2.1 Sample Fabrication

Woven 2 x 2 twill flax fabric (FF), with an average thickness of 0.6 mm and a weight of 200 grams per square meter, was used as the reinforcement material. To produce the laminates required for tensile and impact tests, a composite material was formed using five layers of interwoven flax fabrics, which were carefully cut to the appropriate size and dimensions. The fabrication procedure for the flax fibers reinforced with MWCNTs, as utilized in this study, is illustrated in Figure 1. This method ensures uniform distribution and optimal alignment of the flax fibers, enhancing the overall mechanical properties of the composite material.

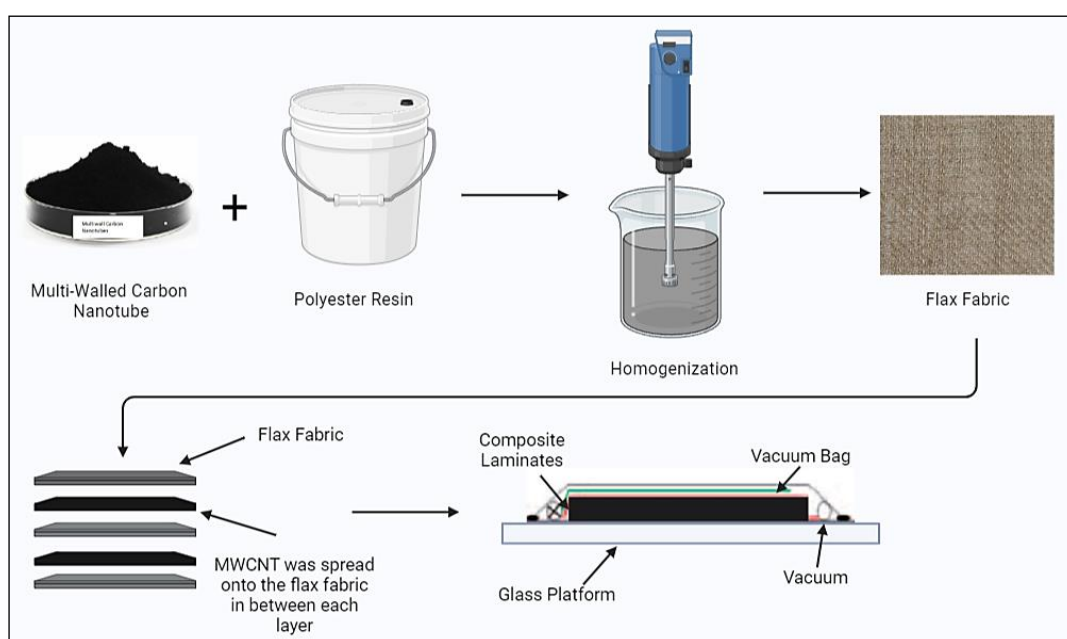


Fig. 1. Fabrication process for composite laminates

For the tensile test, samples were prepared with dimensions of 250 mm x 25 mm, while for the drop-weight impact test, samples were prepared with dimensions of 150 mm x 150 mm. Figure 2 shows the samples for both tests. MWCNTs were mixed with polyethylene (PE) resin using a homogenizer mixer set to 30 minutes and 45 rpm. The mixture was then evenly spread onto the flax fabric between each layer. The final composition percentages are detailed in Table 1.

A vacuum bagging machine was used to fabricate the composite laminates. The composite components were strengthened and void-free through a controlled curing process involving pressure and heat. To establish a connection between the vacuum line and the bag, a suction cup, known as the vacuum port, was used. This port was connected to a small hole punctured in the vacuum bag. During the bagging process, a vacuum was applied to eliminate air from the material. The pressure and temperature were maintained at 0.75 bar and 120°C, respectively. Consistency in these settings was crucial to ensure optimal curing conditions. The temperature was steadily increased to avoid heat shock, and the curing process typically lasted for around two hours under these specified conditions.

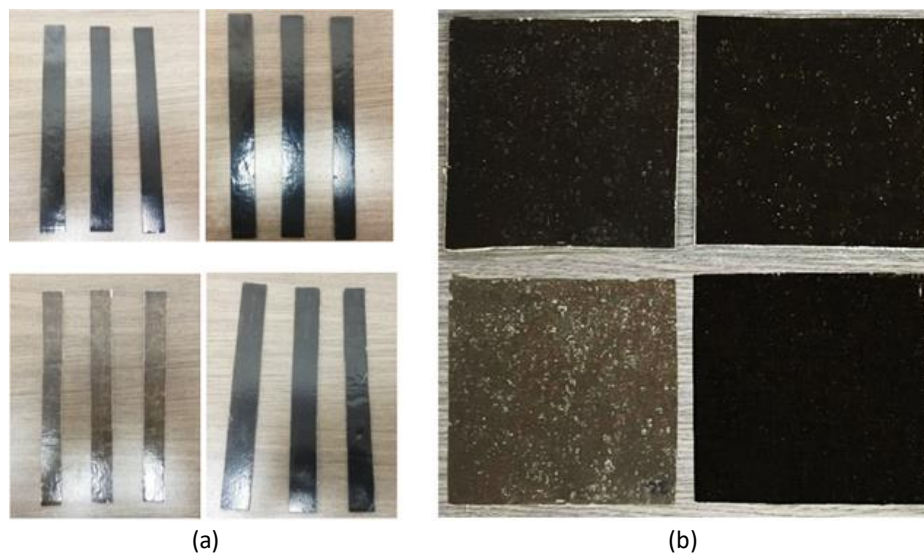


Fig. 2. The flax fiber reinforced composite samples (a) Tensile (b) Drop weigh impact test

Table 1
 Flax sample composition

Sample	Flax (wt. %)	Polyester resin (wt. %)	MWCNT (wt. %)
FF/PE	40	60	0
FF/PE-CNT1	40	59	1
FF/PE-CNT2	40	58	2
FF/PE-CNT3	40	57	3

2.2 Tensile Test

Tensile test was done using an INSTRON 3382 Floor Model Universal Testing Machine in accordance with ASTM D638–14 Standards. The tests were carried out at a rate of 2.0 mm/min.

2.3 Drop-Weight Impact Test

An impact test was conducted at the Faculty of Engineering, Universiti Putra Malaysia using the IMATEK IM10 machine as shown in Figure 3 to replicate a low-velocity impact. The experiment involved five repetitive samples, and the results were recorded using IMATEK Impact Analysis software. To prevent plate rebound during impact, the sample plate was centered relative to a cut-out and firmly secured within a rigid support fixture. A striker, weighing 5.101 kg and featuring a hemispherical tip with a 5 mm radius, was used. The striker's second descent was halted by a rebound catcher. The magnitude of impact energy varied according to the height from which the striker was released on the sample, as described by Eq. (1).

$$E_I = mgh \tag{1}$$

where mass (m) of the impactor is 5.101 kg, gravitational acceleration (g) is 9.81 m/s², and h the height of the impactor. During the experiment, samples were subjected to impact energies of 20 J, 25 J, and 30 J. The IMATEK Impact Analysis software recorded data on peak force and energy absorption for each impact. The energy absorbed during testing indicates the amount of energy required to completely fracture a specimen. This data provided critical insights into the material's

behavior under different impact conditions and its ability to absorb and dissipate energy, which is essential for evaluating the composite's mechanical performance.

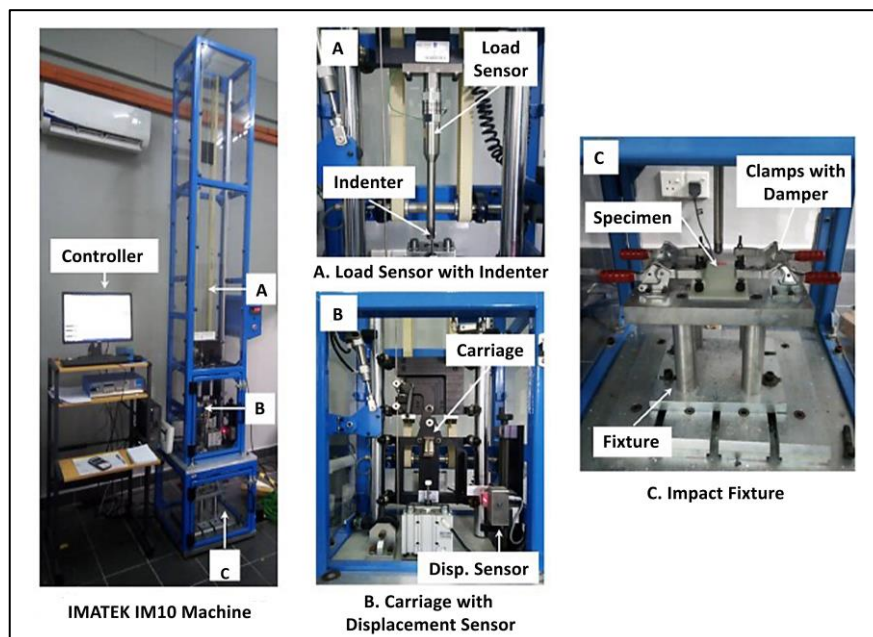


Fig. 3. IMATEK IM10 machine

3. Results

3.1 Effect of MWCNT on Tensile Strength

The tensile strength results, which reflect the material's ability to resist tensile deformation, are presented in Figure 4. The tensile strength values recorded were 85.03 MPa for FF/PE, 80.58 MPa for FF/PE-CNT1, 88.70 MPa for FF/PE-CNT2, and 90.33 MPa for FF/PE-CNT3. Samples FF/PE-CNT2 and FF/PE-CNT3 demonstrated increases in tensile strength by 4.32% and 6.23%, respectively, compared to the control sample FF/PE. Conversely, the FF/PE-CNT1 sample exhibited a 5.32% decrease in tensile strength relative to FF/PE.

The incorporation of MWCNTs into the FF/PE matrix resulted in enhanced stiffness and rigidity for samples FF/PE-CNT2 and FF/PE-CNT3. This improvement can be attributed to the better dispersion of MWCNTs within the polymer matrix, which facilitates stronger interfacial bonding and more effective load transfer from the matrix to the nanotubes. Dimitrios *et al.*, [16] reported that several factors affect the tensile strength of CNT-filled composites, including the degree of crystallinity and the strength of the connections between polymer chains and CNTs, which promote efficient load transfer.

In contrast, the reduction in tensile strength observed in sample FF/PE-CNT1 is likely due to poor dispersion of CNTs within the polymer matrix. This poor dispersion leads to non-uniform load distribution and weak interactions between polymer chains and CNTs, resulting in inefficient load transfer and diminished mechanical performance. The effectiveness of nanofillers in strengthening materials depends significantly on their quantity and distribution within the matrix.

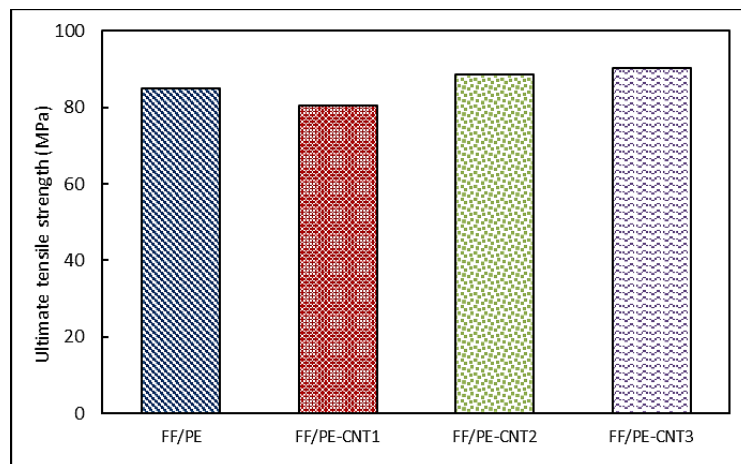


Fig. 4. Samples tensile strength

Scanning Electron Microscopy (SEM) analysis was conducted on samples FF/PE-CNT1 and FF/PE-CNT3 at their respective breaking points during tensile testing, chosen for their highest and lowest UTS values (Figures 5 and 6). Figure 5 reveals that the distribution of MWCNT/PE resins in sample FF/PE-CNT1 is not uniform across the fiber surface. This non-uniformity may result from the vacuum bagging process, which failed to distribute the MWCNT/PE resins evenly and led to weak van der Waals forces and the absence of covalent bonds. Additionally, agglomeration of carbon nanostructures significantly weakens the bond between hydroxyl groups in cellulose and the nanostructures, as observed in sample FF/PE-CNT1. Zheng *et al.*, [17] indicated that agglomeration adversely affects mechanical properties due to uneven dispersion, which acts as a barrier to load transfer among the grains, thereby reducing the ultimate tensile strength. Hashim *et al.*, [18] also reported that homogeneously distributed MWCNT into the matrix can help reduce crack propagation.

Lavagna *et al.*, [19] stressed the importance of proper CNT dispersion within the polymer matrix to minimize agglomeration in nanocomposite structures. The homogenization process during MWCNT/PE resin preparation is crucial in preventing CNT agglomeration [19]. Pötschke *et al.*, [20] proposed a melt mixing process to minimize agglomeration, as it leads to better CNT dispersion within the polymer matrix. In Figure 6, sample FF/PE-CNT3 shows a clean fiber surface, likely resulting from the effective dispersion of MWCNT/PE resin during the vacuum bagging process. This uniform distribution significantly enhances the composite's mechanical properties. Achieving proper dispersion of MWCNTs is critical as it prevents agglomeration and ensures effective load transfer. A homogeneous distribution markedly improves the composite's mechanical integrity and durability.

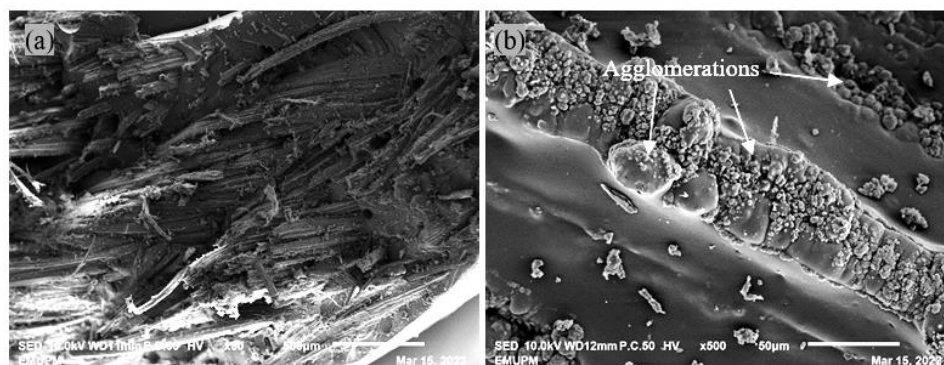


Fig. 5. SEM micrograph of sample FF/PE-CNT1 (a) 50x of magnification (b) 500x of magnification

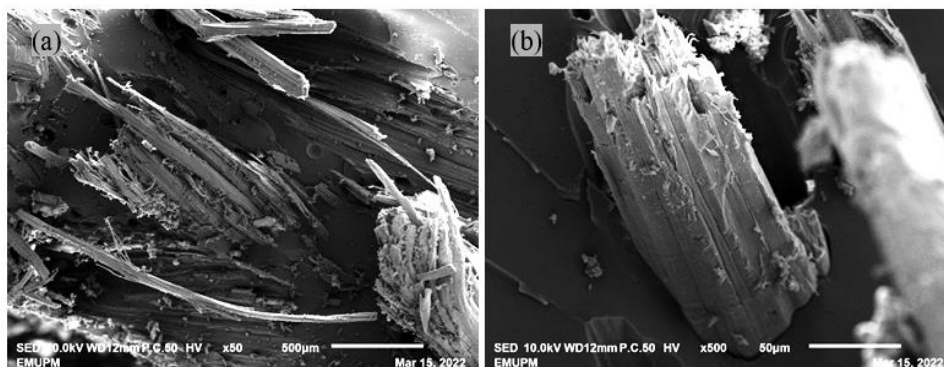


Fig. 6. SEM Micrograph of the sample FF/PE-CNT3 (a) 50x of magnification (b) 500x of magnification

3.2 Low-Velocity Impact Test

An impact test was conducted following the determination of the tensile strength of each composite. The energy absorption, peak force, and force-displacement curves were analyzed to assess the stiffness and impact resistance of each material.

3.2.1 Energy absorption characterization

The results of the drop-weight impact test, including energy absorbed (J), peak force (kN), and maximum displacement at different energy levels (20 J, 25 J, and 30 J), are presented in Table 2. The energy absorption outcomes are illustrated in Figure 7. The data indicate a clear correlation between impact energy and the amount of energy absorbed by each sample, highlighting the material's capacity to dissipate energy under impact conditions, which is crucial for evaluating the performance and durability of the composites.

The energy absorbed by a specimen during an impact test is equivalent to the energy required to create damage within the material. Higher absorbed energy indicates a material's superior ability to absorb and dissipate energy during impact, which is critical for applications requiring high impact resistance and durability. This characteristic means the material can withstand higher forces without fracturing, reflecting better toughness and resilience.

Table 2
 Drop weight impact test analysis

Sample	Impact energy (J)	Energy absorbed (J)
FF/PE	20	24.11
	25	31.53
	30	33.85
FF/PE-CNT1	20	27.31
	25	35.64
	30	37.59
FF/PE-CNT2	20	29.45
	25	36.73
	30	37.64
FF/PE-CNT3	20	34.43
	25	41.56
	30	43.81

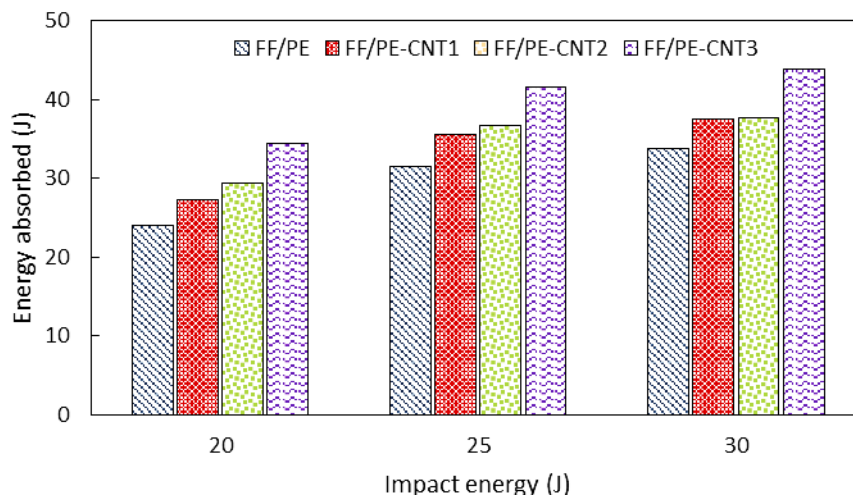


Fig. 7. Energy absorbed for samples at different impact energy

An increasing trend in energy absorption with higher MWCNT content was observed in samples FF/PE-CNT1, FF/PE-CNT2, and FF/PE-CNT3. Specifically, FF/PE-CNT3 exhibited the highest energy absorption across various impact energies, with values of 34.43 J, 41.56 J, and 43.81 J. Compared to FF/PE, the energy absorbed by FF/PE-CNT2 increased by 42.80%, 29.42%, and 31.81% at impact energies of 20 J, 25 J, and 30 J, respectively. The significant improvement in energy absorption is attributed to the exceptional mechanical properties of MWCNTs, which enhance load transfer and distribution. MWCNTs increase the composite's stiffness and strength by providing a larger surface area for stress distribution, thereby reducing stress concentrations. Their high aspect ratio and excellent interfacial bonding with the polymer matrix facilitate effective energy dissipation during impact. Additionally, the uniform dispersion of MWCNTs ensures even load distribution, minimizing the likelihood of failure and enhancing the overall durability of the composite [21]. Kurian *et al.*, [22] suggest that crosslinking or functionalization techniques can further enhance interfacial interactions within composite systems containing these nanoparticles.

However, it should be noted that uneven distribution or poor dispersion of CNT powder within PE can lead to agglomeration issues, negatively impacting material performance. Moreover, incorporating woven-type flax fabric fibers into composite materials not only improves force distribution but also enhances impact resistance compared to other fiber types, such as random and unidirectional ones. This is due to the inherent impact-resistant properties of woven flax fabrics, which significantly contribute to improving the mechanical characteristics of composites. Furthermore, using renewable fiber sources like flax ensures sustainable production while maintaining consistent specific mechanical performance.

In our study, the higher absorbed energy in sample FF/PE-CNT3 demonstrates its enhanced ability to handle impact forces effectively. This is vital for performance-critical applications such as aerospace, automotive, and defence industries, where materials must maintain structural integrity under extreme conditions. This improvement is supported by research showing that the incorporation of reinforcements like MWCNTs into composite materials enhances their energy absorption capabilities. Effective dispersion and strong interfacial bonding between CNTs and the matrix contribute to this increased performance, allowing the composites to dissipate more energy and exhibit better overall mechanical properties [23-25].

3.2.2 Force-displacement curve

The force-displacement curves acquired from the IMATEK IM10 data acquisition system for each specimen are presented in Figure 8(a) for 20 J, (b) for 25 J and (c) for 30 J. As shown in Figure 8, the curves for all samples at different energy levels form closed loops, indicating that the specimens did not experience penetration, as the incident energy was fully transferred back to the specimen at the point of maximum displacement. After reaching maximum displacement, the specimens transferred the elastically stored impact energy back to the impactor. The maximum deflection for each sample is identified from the graph at the point where the force curve returns to zero.

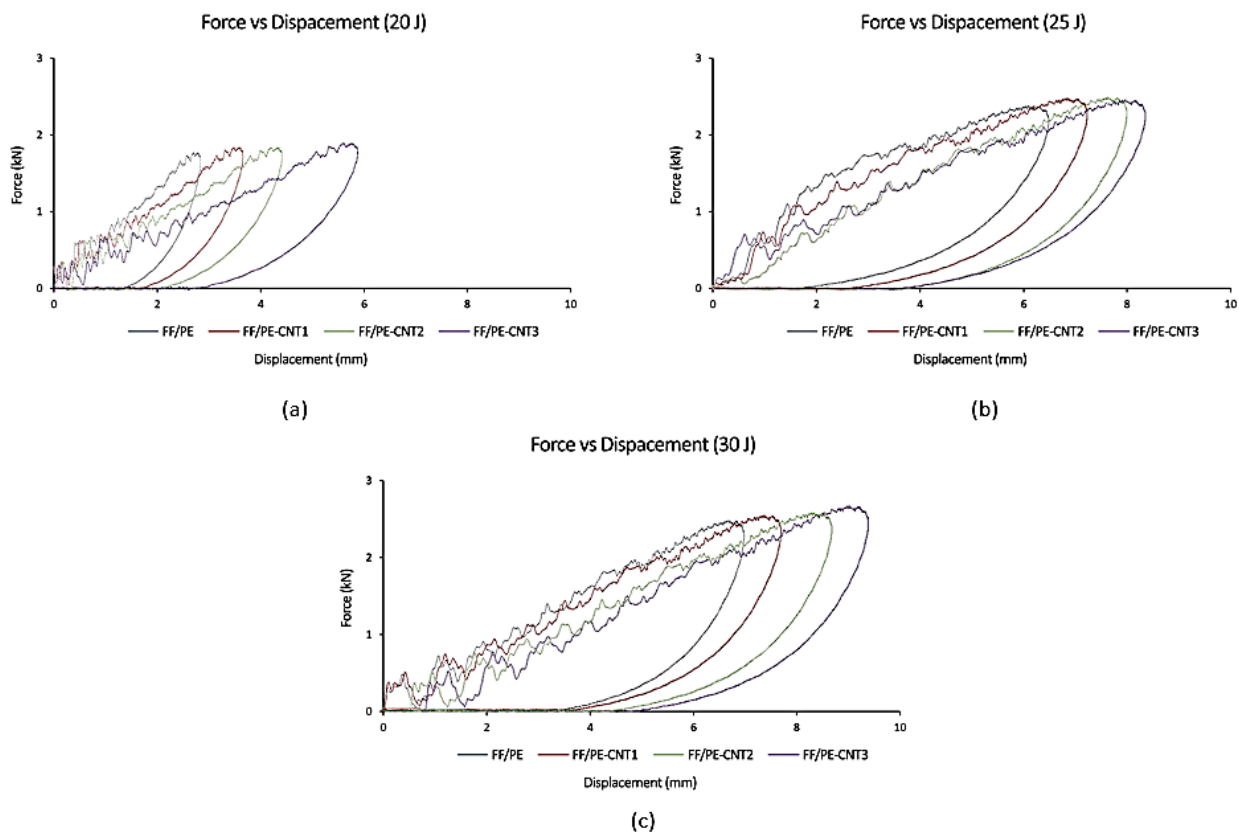


Fig. 8. Force vs displacement (a) 20 J (b) 25 J (c) 30 J

The closed-loop nature of the force-displacement curves indicates the elastic recovery of the material. The initial linear portion of the curves represents the elastic deformation region, where the material deforms but returns to its original shape upon unloading. The peak of each curve signifies the maximum force the material can withstand before significant damage occurs. The area within the loop provides an indication of the energy absorbed by the specimen during impact. This characteristic is essential for understanding the material's ability to endure and dissipate impact energy.

Furthermore, the curves' shapes and the differences in maximum deflection values provide insights into the material's stiffness and ductility. Samples with higher MWCNT content, such as FF/PE-CNT2 and FF/PE-CNT3, show higher peak forces and greater deflections, indicating improved impact resistance and energy absorption capabilities. The uniform dispersion of MWCNTs in these samples likely contributes to the enhanced load transfer and distribution, minimizing the risk of failure. In contrast, the FF/PE and FF/PE-CNT1 samples exhibit lower peak forces and deflections, suggesting that the presence of MWCNTs alone is insufficient to improve mechanical properties without proper dispersion and bonding.

The values of maximum deflections are summarized in Table 3. Overall, the force-displacement analysis confirms that MWCNT reinforcement enhances the mechanical performance of flax fiber composites, particularly in terms of impact resistance and energy absorption, making them suitable for applications requiring high durability and resilience.

Table 3
 Maximum displacement of all samples

Sample	Impact energy (J)	Maximum displacement (mm)
FF/PE	20	2.89
	25	6.46
	30	6.91
FF/PE-CNT1	20	3.66
	25	7.25
	30	7.90
FF/PE-CNT2	20	4.39
	25	8.02
	30	8.37
FF/PE-CNT3	20	5.89
	25	8.37
	30	9.35

3.2.3 Low-velocity impact peak force

The force-time plots illustrate the material's ability to absorb and redistribute energy under impact conditions. The peak force values are indicative of the material's resistance to initial damage, while the subsequent load drop signifies its ability to dissipate energy and prevent catastrophic failure. The force-time plots for each specimen are presented in Figure 9, with 9(a) representing 20 J, 9(b) representing 25 J, and 9(c) representing 30 J impact energies.

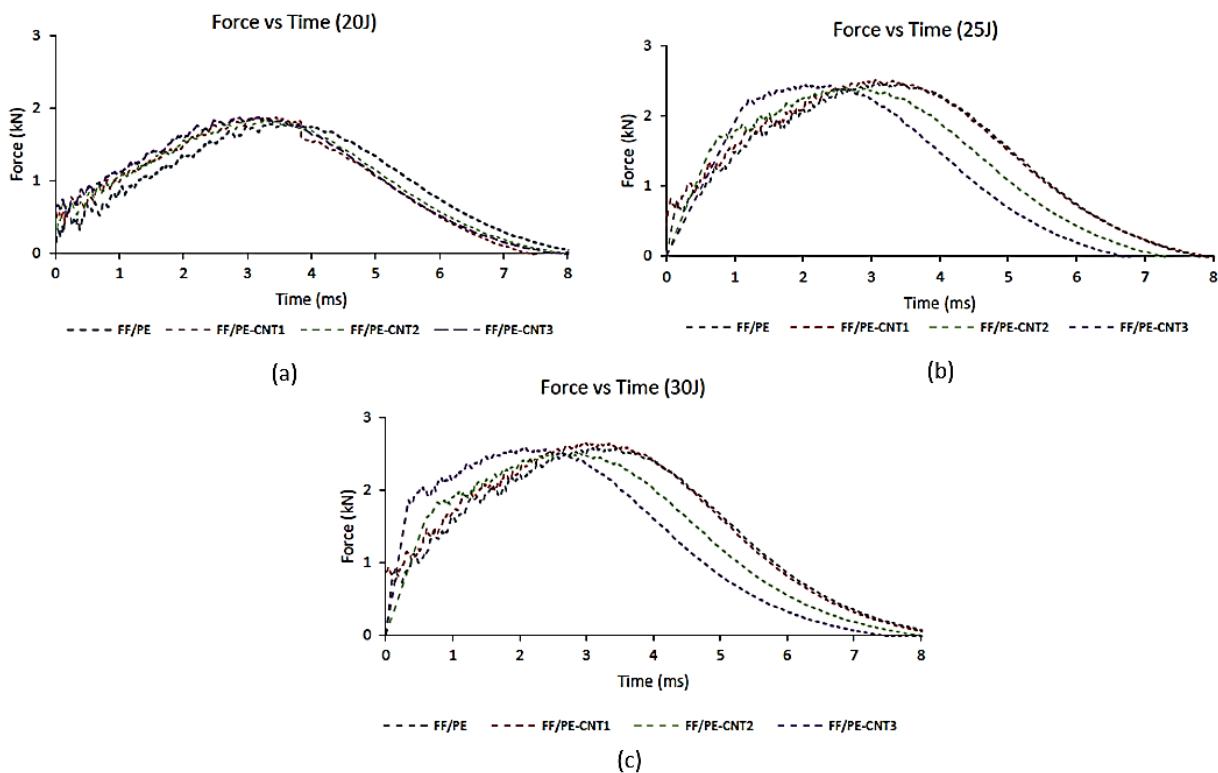


Fig. 9. Force vs time (a) 20 J (b) 25 J (c) 30 J

As shown in Figure 9, the initial part of the graph, where force increases linearly with time, indicates the elastic behavior of the material. In Figure 9(a), the force increases steadily, compared to the sharper increase at energy levels of 25 J and 30 J. This region demonstrates how the material initially responds to the impact without any permanent deformation. The small oscillations observed in all samples are due to early damage initiation, such as the formation of micro-cracks and delamination within the material. These oscillations reflect minor structural disruptions as the impact progresses. Among the samples, the FF/PE-CNT3 shows the best elastic behavior, as evidenced by the smoother and more gradual increase in force compared to the sharper increases observed in other samples. This smoother increase indicates a more uniform stress distribution and better elastic response before significant damage initiation. The reduced oscillations in FF/PE-CNT3 further support its superior ability to maintain structural integrity under initial impact conditions.

The first peak force represents the maximum force the material can withstand before significant damage occurs. Following the first peak force, a load drop is observed for all samples. This drop indicates the failure of the material's front face sheet or the breakage of fibers. The extent and rate of the load drop provide insights into the material's damage tolerance and failure mechanisms. Higher peak forces and smoother load drops in samples with higher MWCNT content suggest enhanced mechanical properties, including better load distribution and increased energy absorption capacity. The summary of the peak force is shown in Table 4 with the highest is sample FF/PE-CNT3.

Table 4
 Peak force of all samples

Sample	Impact energy (J)	Peak force (kN)
FF/PE	20	1.78
	25	2.39
	30	2.51
FF/PE-CNT1	20	1.82
	25	2.44
	30	2.57
FF/PE-CNT2	20	1.83
	25	2.47
	30	2.59
FF/PE-CNT3	20	1.87
	25	2.51
	30	2.65

The peak force increased with rising impact energy for all samples. The control sample FF/PE showed peak forces of 1.78 kN, 2.39 kN, and 2.51 kN at impact energies of 20 J, 25 J, and 30 J, respectively. Samples FF/PE-CNT1, FF/PE-CNT2, and FF/PE-CNT3 all exhibited an increasing trend in peak force compared to the control. Notably, FF/PE-CNT3 performed the best, with peak forces of 1.87 kN, 2.51 kN, and 2.65 kN at the respective impact energy levels. The concentration of CNTs plays a crucial role in determining the material stiffness and overall mechanical properties of FF/PE. Tehrani *et al.*, [26] demonstrated that adding 2 wt.% of MWCNTs can improve failure strain without significantly affecting the tensile properties along the fiber orientation during quasi-static processes. When MWCNTs are well-distributed throughout the composite structure, exhibiting a good aspect ratio and strong adhesion between the matrix and filler materials, they enhance the composite's strength, elastic modulus, and fatigue resistance. This effective reinforcement capability is critical for next-generation fiber-matrix composite materials. Additionally, strong interfacial bonding between the fibers and the MWCNT matrix enhances load transfer efficiency, improving peak force.

4. Conclusions

This study has demonstrated the significant potential of multi-walled carbon nanotube (MWCNT) modification to enhance the mechanical properties of flax fiber-reinforced composites. The incorporation of MWCNTs through a vacuum bagging process has shown notable improvements in both tensile strength and impact resistance, making these composites viable candidates for high-performance applications.

- i. Tensile testing results indicate that MWCNTs, when uniformly dispersed within the flax fiber composite matrix, can substantially increase the material's tensile strength. Specifically, the FF/PE-CNT3 sample exhibited a 6.23% improvement in tensile strength compared to the control sample (FF/PE), highlighting the effectiveness of MWCNTs in reinforcing natural fiber composites.
- ii. Low-velocity impact testing further revealed that MWCNT-modified composites possess superior energy absorption capabilities. The FF/PE-CNT3 sample absorbed 43.81 J at a 30 J impact energy, representing a 31.81% increase over the control sample. This enhancement is attributed to the improved load transfer and interfacial bonding provided by the MWCNTs, which distribute stress more effectively throughout the composite structure.
- iii. SEM analysis confirmed that proper dispersion and integration of MWCNTs play a crucial role in achieving these mechanical enhancements. Samples with better MWCNT dispersion exhibited fewer instances of agglomeration and more consistent mechanical properties.

In conclusion, the addition of MWCNTs to flax fiber-reinforced composites significantly enhances their mechanical performance, particularly in terms of tensile strength and impact resistance. These findings suggest that MWCNT-modified flax fiber composites are promising materials for applications in aerospace, automotive, and other industries requiring high strength and durability. Future research should focus on optimizing the fabrication process and exploring the long-term durability and environmental impact of these advanced composites.

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