# Advanced Composite Materials Development for Aerospace Applications: The Key Role of MWCNTs in Performance Improvement

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## ABSTRACT

**This study explores the effect of adding Multi-Walled Carbon Nanotubes (MWCNTs) to epoxy matrices to meet the need for more robust and lighter composite materials for aerospace applications, focusing on acetone utilization as a solvent to improve nanotube dispersion. The experimental method included ultrasonication for effective MWCNT dispersion in acetone, followed by their incorporation into epoxy resin via filament winding. Comprehensive mechanical testing and morphological characterization were also carried out deploying tensile testing and Scanning Electron Microscopy (SEM). The results demonstrated that integrating MWCNTs significantly enhanced the mechanical properties of the composite material, including ultimate tensile strength, Young's modulus, and elongation at break. This improvement was especially pronounced at a 1% MWCNT concentration, exhibiting a tensile strength increase of up to 102% compared with pure epoxy. The analysis of fracture surfaces via SEM revealed that homogeneously distributed MWCNTs effectively reduced delamination, enhancing resistance to crack propagation. These findings provide critical insights into fabrication techniques, offering potential**

**advancements in composite manufacturing processes that could significantly improve fuel efficiency and payload capacity in aerospace applications.**

***Keywords-aerospace applications; fabrication techniques; fracture surface; mechanical properties; multi-walled carbon nanotubes***

## I. INTRODUCTION

The use of Polymer Matrix-Based Composite materials (PMCs) is becoming increasingly common in a variety of applications, including the automotive, aerospace, and defense industries due to their advantages over conventional metal materials, such as lower density, lower production costs, high corrosion resistance, and more straightforward processing methods [1]. In particular, owing to their superior mechanical strength, heat resistance, chemical resistance, and strong adhesion, thermoset polymers, like epoxy resins, have been widely employed as polymer matrices in composites, such as Carbon Fiber Reinforced Polymer (CFRP) [2]. However, the high crosslink density in epoxy resins limits the movement of molecular chains, resulting in low tensile strength and thermal stability [3].

In the aerospace industry, there is a continuous demand for innovative composite materials to improve performance, especially for components, such as rocket bodies (launch vehicle fuselage) that must endure extreme loads and pressure during a flight [4]. Recent studies have shown that although carbon fiber is effective in strengthening composite matrices, MWCNT addition offers significant potential to further improve the mechanical and thermal properties of these composites [5].

MWCNTs have unique characteristics, such as high aspect ratio, outstanding tensile strength, and high Young's modulus, making them promising additives for composite matrices [6, 7]. The integration of MWCNTs has significantly increased the tensile strength of the carbon fiber-reinforced composite matrices, outperforming conventional composites. Filament winding is the preferred manufacturing method for aerospace component production, which is benefited from integrating MWCNTs. However, an exact parameter optimization is necessary to guarantee an even dispersion and a strong adhesion in the matrix [8].

Several studies have shown that MWCNT addition to epoxy matrices can significantly improve the mechanical properties of composites, especially tensile strength [9]. This increase is due to the ability of nanotubes to increase the cross-link ratio and inhibit the movement of molecules in the epoxy matrix, resulting in a more robust composite structure [10]. However, dispersion techniques play a crucial role in achieving these benefits [11]. Ultrasonication has been identified as an effective method for dispersing MWCNTs in epoxy matrices, although process parameters, such as sonication time, frequency, and the use of solvents, like acetone, must be carefully controlled to prevent damage to the nanotubes and ensure optimal reinforcement [12, 13].

Acetone utilization can significantly enhance the mixing and distribution of carbon-based fillers within the epoxy, promoting uniformity and stability in the resultant nanocomposite. Acetone's rapid evaporation during the curing process allows for improved mechanical properties, as nanofillers remain well-dispersed without compromising the integrity of the epoxy network [14, 15]. Compared to other solvents, like toluene or tetrahydrofuran, acetone demonstrates a less profound alteration of the mechanical behavior of cured materials [16]. When using acetone in the dispersion of Carbon Nanotubes (CNTs) within the epoxy matrix, it is observed that the resultant composites exhibit varied compressive behaviors depending on the degree of filler dispersion achieved [17].

The novelty of this research lies in the filament winding method application with parameter optimization, to achieve uniform dispersion of MWCNTs and their strong adhesion in epoxy matrices, aiming to improve the mechanical strength and thermal stability of carbon fiber-based composite materials. The study also provides a comprehensive analysis of the effect of varying MWCNT concentrations (0.25%-1%) on the mechanical and thermal properties of composites, since the right MWCNT addition level significantly increases tensile strength and resistance to delamination, which are common issues in carbon fiber composites. Moreover, the use of ultrasonication techniques with acetone solvent media is considered effective for producing more homogeneous dispersions and improving the mechanical and thermal properties of composites compared to solvent-free methods. The former is a new contribution to composite fabrication techniques. The study additionally provided detailed characterization using SEM before and after tensile tests, which demonstrated reduced delamination in composites with MWCNTs and a better understanding of the increasing interlaminar strength mechanism. Besides its theoretical contributions, this research provides practical implications in terms of composite material development for aerospace application structures, where the addition of MWCNTs can reduce layer thickness without decreasing its strength, thus contributing to fuel efficiency and increased payload capacity in aerospace applications.

## II. METHODOLOGY

This study utilized various materials to prepare epoxy composites reinforced with MWCNTs. The epoxy resin used was diglycidyl ether of bisphenol A (DGEBA) under Araldite LY 5052, combined with the hardener Aradur 5052, both obtained from Huntsman. MWCNTs with a diameter of 20-40 nm, a length of 10-30 µm, and a purity of 90% were purchased from XFNANO Materials Tech Co. Ltd. (Nanjing, China), and were utilized without further purification. The acetone employed as the solvent was analytically graded and obtained from Merck (Darmstadt, Germany). Furthermore, Tansome H 2550 carbon fiber was deployed to reinforce the composite matrix.

The samples utilized in this research were made from neat epoxy, MWCNTs, and acetone in different compositions. The epoxy resin-hardener ratio used in this experiment was 100:38.

The epoxy resin was mixed with varying proportions of MWCNTs and acetone. Table I shows the sample's codification, due to different amounts of epoxy resin, MWCNTs, and acetone.

TABLE I. CODIFICATION AND FORMULATION OF SAMPLES

| **Samples** | **Substrates** | **MWCNTs (wt%)** | **Acetone (wt%)** |
|---|---|---|---|
| NE | Neat epoxy | - | - |
| EM0.25 | Epoxy/MWCNTs | 0.25 | - |
| EM0.5 | | 0.50 | - |
| EM0.75 | | 0.75 | - |
| EM1 | | 1 | - |
| EM0.25A | Epoxy/MWCNTs/ acetone | 0.25 | 10 |
| EM0.5A | | 0.50 | 10 |
| EM0.75A | | 0.75 | 10 |
| EM1A | | 1 | 10 |

The fabrication process for epoxy/MWCNT composite specimens involved mixing the epoxy (Araldite LY5052-1) and hardener (Aradur 5052) in a 100:38 weight ratio, followed by stirring the mixture for 5 min and pouring it into molds according to ASTM D638-1 standards. The molds were then left to harden at room temperature for 48 h. The manufacturing process also included the addition of various concentrations of MWCNTs into the epoxy matrix, followed by mixing, degassing, and hardening. The degassing process was performed via the vacuum process for 4 hours at -0.95 atm and 60° C. Ultrasonication was carried out for 1 hour at 40 kHz and at room temperature. A similar process was performed using an acetone solvent.

The filament winding method was deployed to fabricate composite samples for mechanical testing using a different matrix, as shown in Figure 1. Carbon tow was passed through a resin bath to be impregnated with resin containing different MWCNT additions. The impregnated carbon tow was then wound onto a molding plate arranged by the delivery head. The angle of winding used in this research was hoop angle.

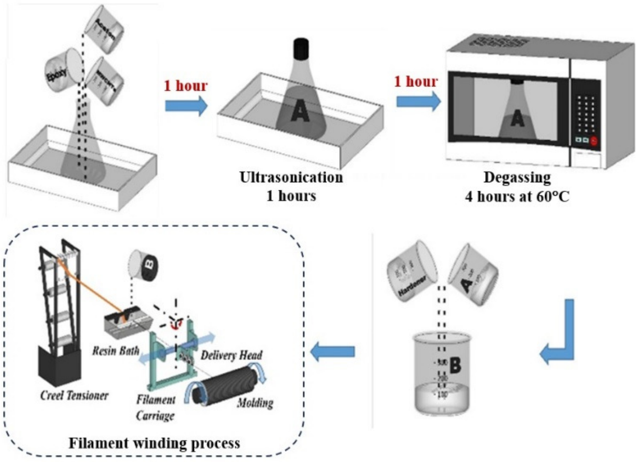

Fig. 1. Filament winding processes.

To ensure the production of high-quality components, an additional procedure was conducted after the wet-winding process [18]. Compression molding was carried out to achieve the desired composite plate. This step not only facilitates the creation of uniform components, but also enhances the mechanical properties of CFRP. The schematic of the processes performed after filament winding is displayed in Figure 2.

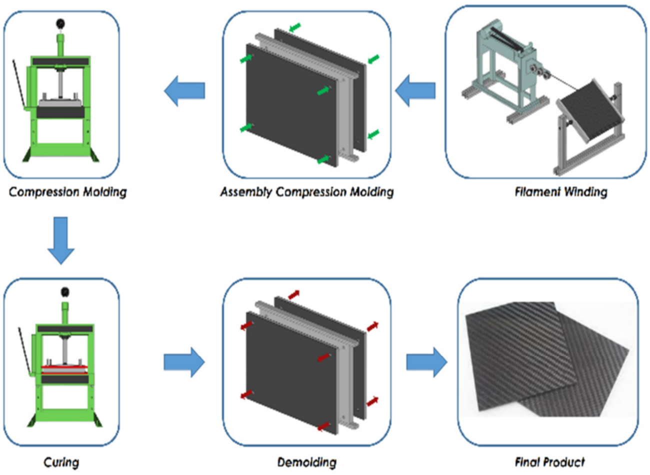

Fig. 2. Curing processes after wet winding.

The Mechanical Test was carried out on a test machine (Shimadzu 50 kN XPlus) with a pulling speed of 5 mm/min. The test specimen was a dog bone, according to the ASTM D638 standard. Testing was performed on five specimens for each sample to ensure the reproducibility of the results, and the average values were presented.

To precisely evaluate how the addition of MWCNTs to carbon fiber composites affects these specific mechanical properties, ASTM D 3039 testing was performed on samples with a pulling rate of 2 mm/min and dimensions of 250 mm x 15 mm. The test machine was a Shimadzu 50 kN XPlus. SEM analysis was carried out to observe the dispersion of MWCNTs in the epoxy matrix and the morphology of the fault surface after the tensile test. The test tool utilized was a SEM (Phenom Pro X). The specimen production process is provided in Figure 3.

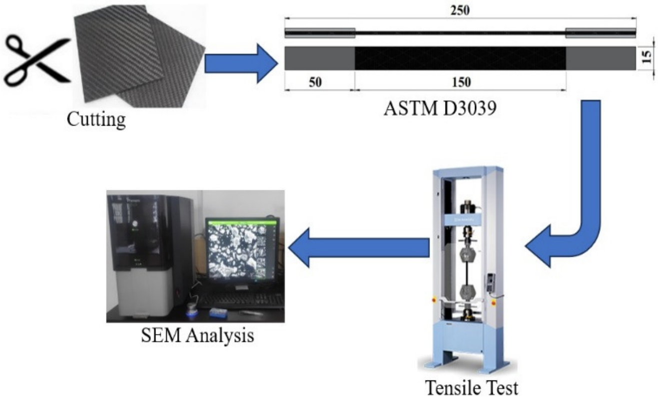

Fig. 3. Specimen production process.

## III. RESULTS AND DISCUSSION

The tensile tests on the neat epoxy, epoxy/MWCNT, and epoxy/MWCNT/acetone composites demonstrated that the composites exhibited brittle failure under applied loading. MWCNT addition increased brittleness, whereas acetone addition decreased brittleness and increased flexibility. Furthermore, the addition of acetone to the epoxy resin reduced its viscosity. The lower viscosity of the epoxy resin increased the flexibility of the composites by reducing their stiffness [19]. The use of acetone as a solvent and the weight percentage of MWCNTs in epoxy composites significantly improved tensile properties, such as ultimate tensile strength, Young's modulus, and strain at break. Table II lists the average tensile properties and standard deviations of the samples.

TABLE II. AVERAGE TENSILE PROPERTIES OF DIFFERENT SAMPLES

| Samples | UTS (MPa) | Young's modulus (GPa) | Strain at break (%) |
|---|---|---|---|
| NE | 19.16 | 2.02 | 1.66 |
| EM0.25 | 19.31 | 1.36 | 1.56 |
| EM0.5 | 20.19 | 1.18 | 1.85 |
| EM0.75 | 27.87 | 1.83 | 1.74 |
| EM1 | 27.87 | 1.65 | 1.86 |
| EM0.25A | 34.88 | 1.56 | 2.32 |
| EM0.5A | 37.69 | 1.61 | 2.44 |
| EM0.75A | 32.89 | 2.10 | 2.62 |
| EM1A | 38.78 | 2.10 | 2.86 |

Both MWCNT percentage by weight and acetone utilization as a solvent affected the tensile properties of the composites compared with neat epoxy. The stress-strain curves of the tensile test are shown in Figure 4.

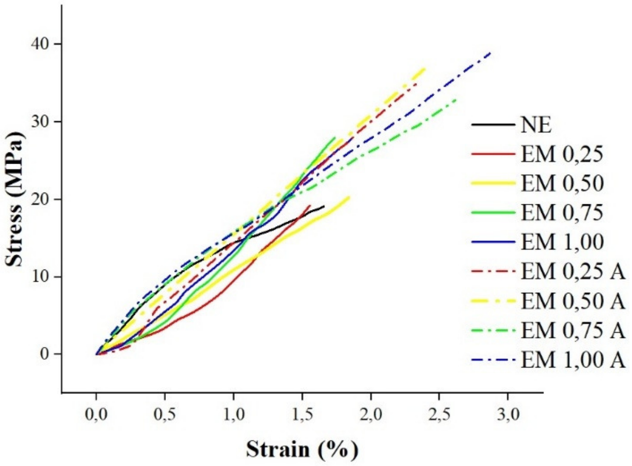

Fig. 4. Tensile properties of neat epoxy, epoxy/MWCNTs, epoxy/MWCNTs/acetone composites - Tensile stress-strain curves.

Figure 5 depicts the Ultimate Tensile Strength (UTS) of the samples. In the epoxy/MWCNT composites, no significant difference in UTS was observed between EM0.25 and EM0.5. The most notable improvement was noted in the EM0.75 and EM1 samples containing 0.75 and 1 wt.% MWCNTs, respectively, which exhibited an approximately 45% increase in UTS compared to neat epoxy. This enhancement can be attributed to the MWCNT incorporation into the epoxy matrix, which enhances the cross-linking ratio and restricts the epoxy molecular motion, thereby improving the UTS of the epoxy/MWCMWCNT composites compared with that of neat epoxy [20]. Improvements in the dispersion of MWCNTs in the epoxy matrix and the strong bonding between MWCNTs and the epoxy, enhanced the UTS composite. This is because nanotubes tend to alter crack propagation [21, 22].

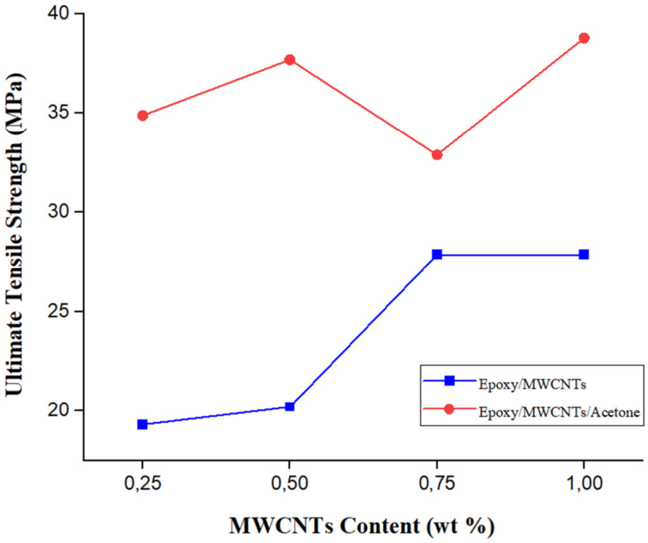

Fig. 5. Ultimate Tensile Strength (UTS).

The epoxy/MWCNT–acetone composites were prepared using acetone as a solvent. This helped the MWCNTs spread more widely, making the material stronger. The composites were much stronger than the NE in almost all the mixtures. Additionally, the strength of EM0.25A, EM0.5A, and EM0.75A samples increased by 82%, 97%, and 72%, respectively. The EM1A samples, which contained 1 wt.% MWCNTs and acetone, were the strongest ones, showing a 102% increase in strength compared to NE. The addition of solvent to the epoxy matrix can lower the resin viscosity, enabling better distribution of MWCNTs within the epoxy matrix [23].

The addition of 0.5% MWCNTs to epoxy was also investigated in other studies. In this present work, the incorporation of 0.5% MWCNT into epoxy resin was conducted employing two distinct approaches: one utilizing acetone as an aid and the other not. In [20] an 8% increase in tensile strength was found when 0.5% MWCNT was added to epoxy. In contrast to the present study, the tensile strength of epoxy reinforced with 0.5% MWCNTs increased by 5% when the dispersion was carried out without the aid of acetone. Epoxy tensile strength was augmented by 0.5% MWCNTs, which had undergone a dispersion process assisted by acetone, having demonstrated a notable increase of up to 97%.

MWCNT addition and the use of acetone as a solvent also affected Young's modulus, as illustrated in Figure 6. The

Young's modulus decreased for most samples compared with neat epoxy, except for EM0.75A and EM1A, each of which showed a 5% increase. The increase in Young's modulus may be due to the addition of MWCNTs that limit the movement of polymer chains under load [20].

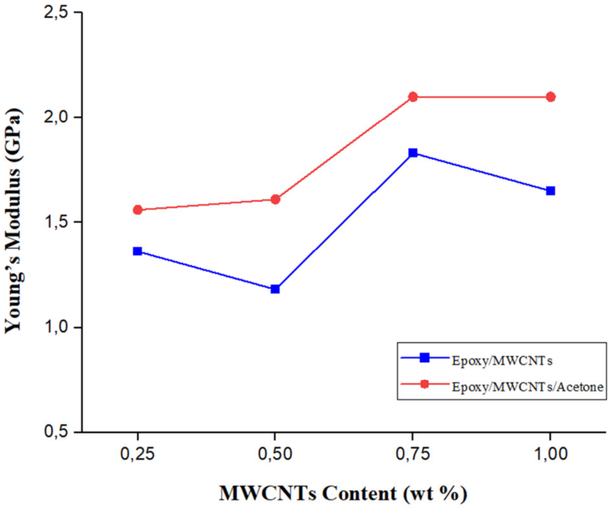

Fig. 6. Young's modulus.

The results of this study are consistent with those of another research on Young's modulus [20] where it was demonstrated that incorporating MWCNTs resulted in a 12-21% rise in Young's modulus. It was also found that the Young's modulus rose by 5% in the presence of 0.75% and 1% additions. This trend is mirrored by an increasing Young's modulus, albeit with varying values.

Figure 7 shows that the strain at break of the composites was affected by the MWCNT weight percentage and the use of acetone as a solvent. In the epoxy/MWCNT composites, the strain at break decreased by approximately 6% for the EM0.25 sample, whereas the other samples demonstrated increases of approximately 11%, 5%, and 11% compared to NE. For the epoxy/MWCNT/acetone composites, the strain at break increased linearly with the addition of MWCNTs, showing increases of approximately 40%, 47%, 58%, and 72% compared to NE. These results indicate enhanced interfacial adhesion between the nanotube and epoxy matrix due to the homogeneous dispersion of MWCNTs into the epoxy [24, 25].

A range of different effects were noted during the tensile test strain, which showed a tendency to increase in both acetone and non-acetone dispersions throughout the study. In contrast to the findings of [20], there was a tendency for the tensile strain to decrease. This uptick can be attributed to the effective interaction between the MWCNTs and the reinforcement fibers at the interface [24].

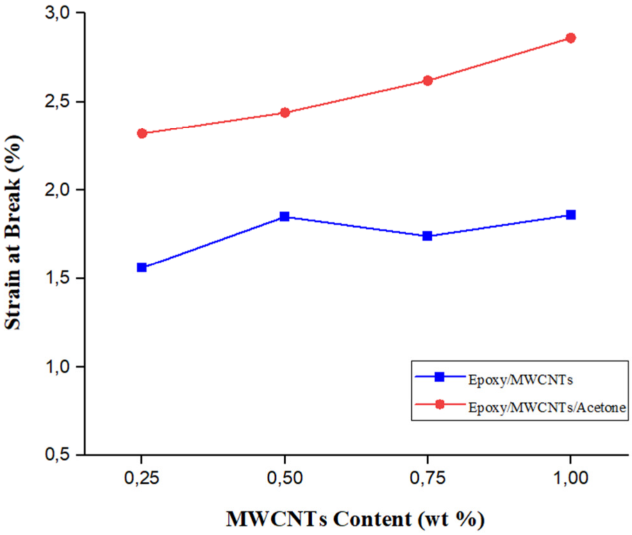

Fig. 7. Strain at break.

When acetone was added as a solvent, the combination of epoxy and MWCNTs produced more interesting results. The former allowed for a more uniform dispersion of MWCNTs in the epoxy matrix, leading to a more consistent improvement in mechanical properties. The sample containing 1% MWCNTs showed the highest maximum tensile strength, exhibiting a 102% increase compared to the epoxy-treated sample. The elastic modulus also increased with the addition of acetone, indicating that the MWCNTs could reinforce the composite without degrading the material.

The epoxy/MWCNT composites with acetone solvent yielded promising results, as previously discussed. Tensile testing was conducted on the MWCNT specimen using an acetone solvent in CFRP. The testing was performed five times, and the results were averaged to create a stress-strain curve, as depicted in Figure 8. The applied load resulted in a significant decrease in stress without an increase in length at the maximum stress value, indicating brittle properties for each sample.

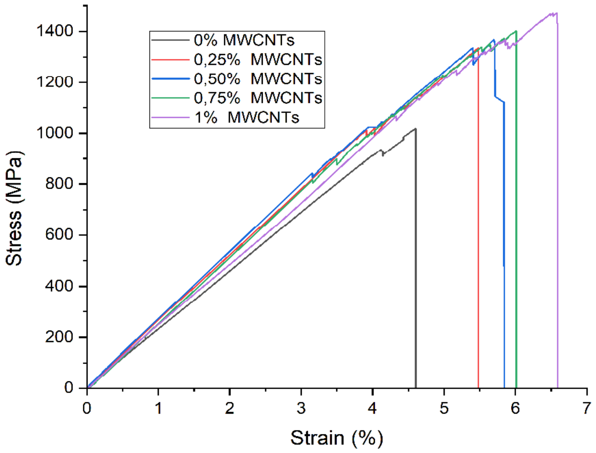

Fig. 8. Stress-strain curve of the composite with various MWCNT additions.

The graph in Figure 8 clearly displays that the stress and strain values are higher when MWCNTs are added at 1% compared to 0%, indicating a significant increase in strength. Adding MWCNTs to the Nanofiller can improve the interlaminar strength [26, 27], as demonstrated by the stable curve when MWCNTs are included. This suggests a reduced likelihood of delamination and a tendency toward simultaneous fracture in the laminate. The stress-strain curve analysis helped determine the maximum tensile strength of each variant, as shown in Figure 9. The maximum tensile strength of the MWCNTs depends on the MWCNT amount added to the material. In the first test (0% MWCNTs), the maximum tensile strength was 1068 MPa. Adding 0.25% MWCNTs increased the maximum tensile strength to 1335 MPa, constituting a 25% improvement. The maximum tensile strength then increased to 1361 MPa in the second test (0.50% MWCNTs), 1.94% higher than the previous result. The third test (0.75% MWCNTs) showed a 4.92% increase, yielding a maximum tensile strength of 1428 MPa. The maximum tensile strength of the fifth test (1% MWCNTs) was recorded at 1487 MPa, indicating a 39.2% increase over the first test, that is, 4.13% higher than the previous test.

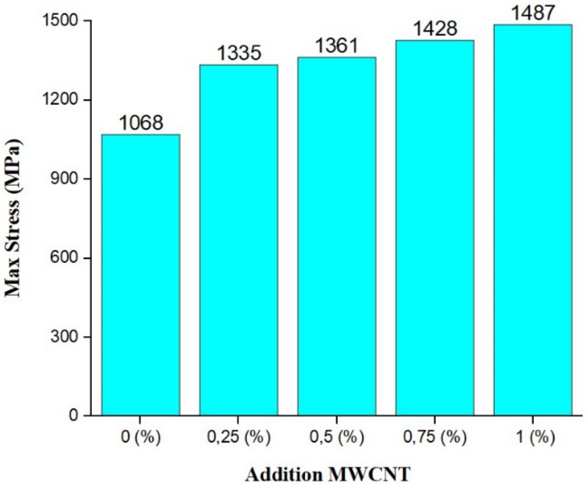

Fig. 9. Maximum tensile strength with various MWCNT additions.

Figure 10 demonstrates the change in the elongation at break for different MWCNT levels in addition to the carbon fiber composite samples. The elongation at fracture ranged from 4.6% to 6.48%, with the highest value having been recorded when MWCNTs were added. This value is vital for evaluating the material's ability to stretch before breaking, especially under high stress. Obtaining the appropriate fracture elongation level is crucial because it depends on the specific application and the material's maximum stress tolerance [28]. The dispersion of MWCNTs in the epoxy was analyzed by SEM. The fracturing surfaces of the samples were observed during tensile testing. Figure 11 (a-i) presents the fracture surfaces of different samples. It was noted that samples with higher MWCNT percentages exhibited rougher surfaces and some aggregation, indicating poor dispersion and weak interfacial adhesion between the MWCNTs and epoxy matrix [29].

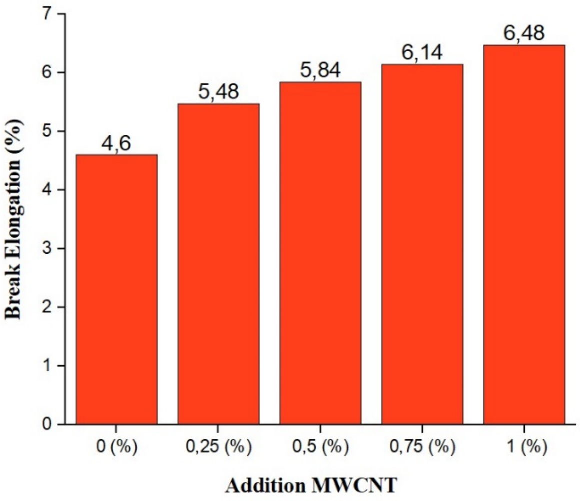

Fig. 10. Value of break elongation with variations in the addition of MWCNTs.

The composites treated with acetone-treated MWCNTs had a rougher surface than those prepared without acetone treatment. The roughness increased as the percentage of MWCNTs increased. The acetone helped reduce the accumulation and promoted the uniform dispersion of MWCNTs in the epoxy matrix. Additionally, the fracture surface of the composites with 0.75% and 1% MWCNTs showed significant tensile deformation, as indicated by cracks, wavy lines, and stress whitening. The addition of MWCNTs and acetone to the epoxy matrix improved the energy dissipation and delamination resistance due to the strong interfacial interaction [30]. The fracture surface of the EM1A sample indicates the high resistance offered by the material to crack propagation, with a rougher surface leading to the toughness of the epoxy [31]. After conducting tensile testing, SEM characterization was performed on the MWCNT specimens in CFRP using acetone. The purpose was to determine the role of adding MWCNTs to the matrix as a nanofiller. The results portrayed in Figure 11 indicate that the carbon fiber composite without MWCNTs exhibited more delamination than the composite with MWCNTs. This is likely due to the lower interlaminar strength of the CFRP composite. Consequently, the incorporation of nanofillers into the CFRP composite matrix improved interlaminar toughness and reduced the occurrence of delamination [32, 33]. The SEM results reveal that the CFRP with the added MWCNTs exhibited less delamination than the composite without the MWCNTs. The MWCNTs were not visible on SEM due to scale limitations. MWCNT influence can be observed in the composite fracture following tensile testing, particularly in the case of 1% MWCNTs, as depicted in Figure 11.

The graph (a) in Figure 12 illustrates how adding MWCNTs affects interlaminar strength. When 1% MWCNTs were added as a nanofiller, no delamination was observed. Thus, the addition of MWCNTs to the composite material reduced the delamination. As a result, the maximum tensile strength achieved was 1487 MPa, as evidenced in Figure 8, which was the highest strength compared to other variations of

MWCNT addition. In Figure 12 (b, c, d), the difference in surface flatness indicates plastic deformation, which increases material toughness, as displayed in Figure 9, where adding 1% MWCNT as a nanofiller resulted in the highest elongation value at the time of fracture compared with the other variations.

The results indicate that adding MWCNTs to the epoxy matrix significantly improves the composite's mechanical properties, especially its tensile strength and deformation ability. The use of acetone solvents effectively enhances MWCNT dispersion, leading to increased maximum tensile strength and elongation at the point of break. The SEM analysis revealed reduced delamination and enhanced crack propagation resistance. This study demonstrated the potential of MWCNTs as a composite material for high-engineering applications, especially in the aerospace industry.

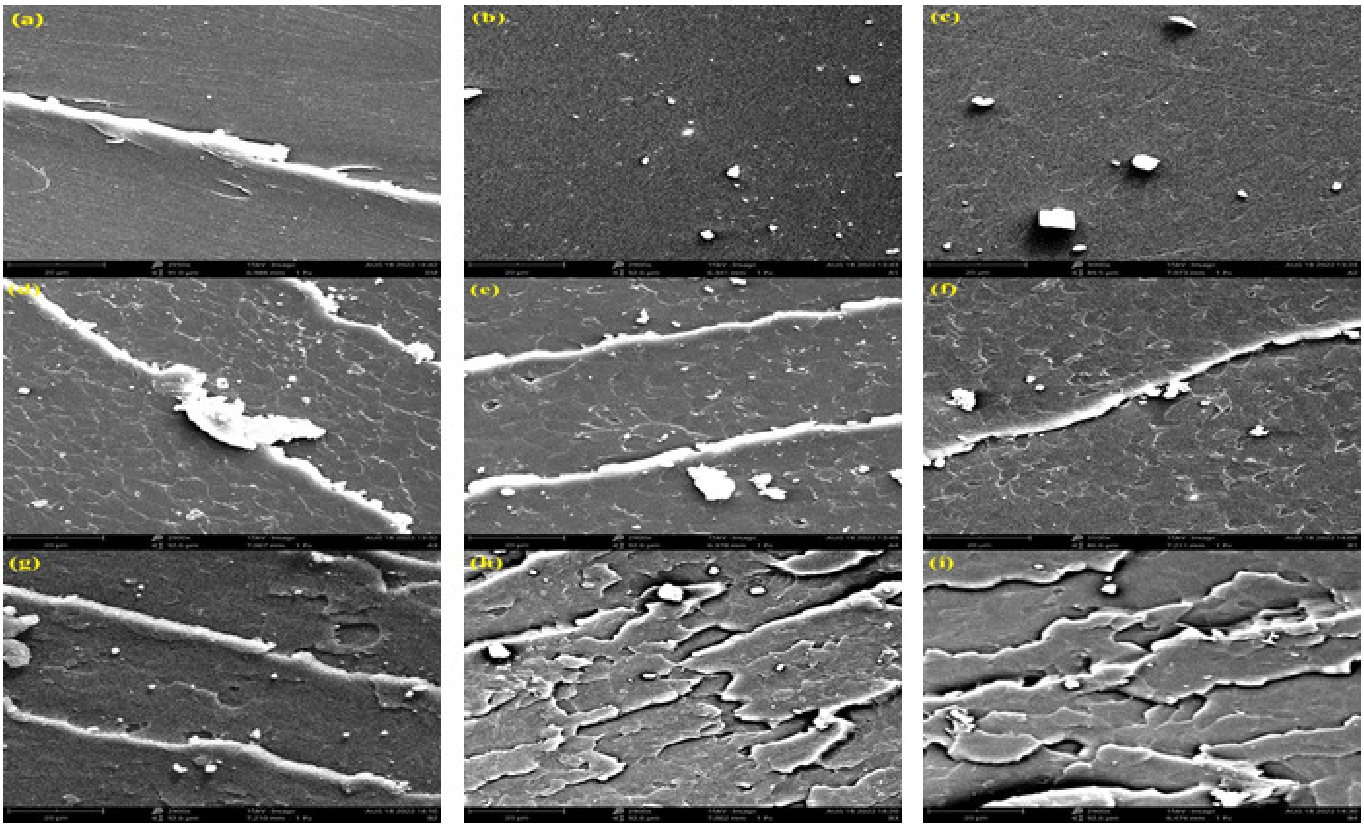

Fig. 11. SEM images of the tensile fracture surface of: (a) NE, (b) EM0.25, (c) EM0.5, (d) EM0.75, (e) EM1, (f) EM0.25A, (g) EM0.5A, (h) EM0.75A, and (i) EM1A samples at a 3000×magnification.

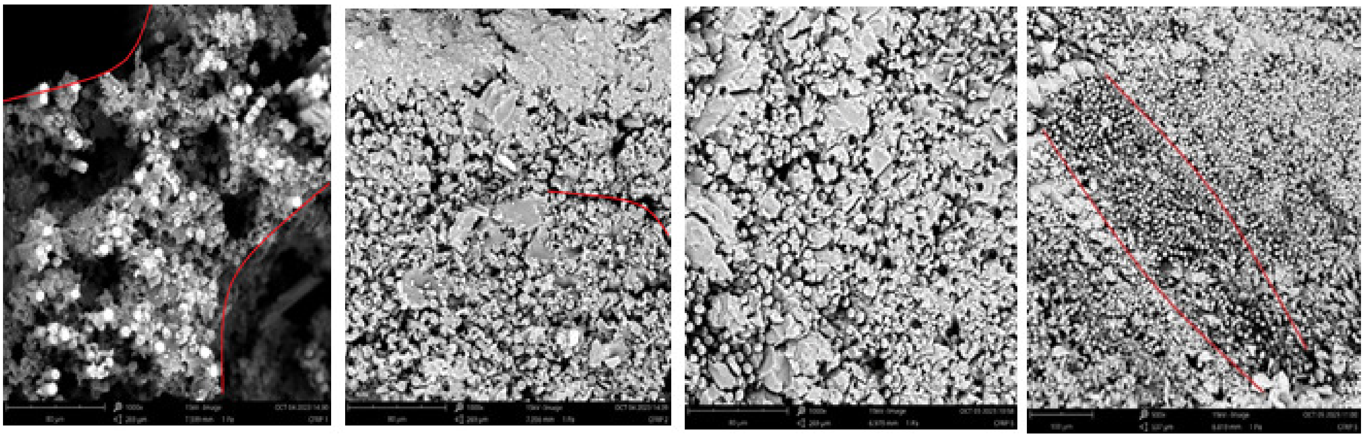

Fig. 12. SEM characterization of the fracture surface of carbon fiber composite specimens (from left ro right): (a) Carbon fiber composite without MWNCTs, (b) carbon fiber composite with MWCNTs, 1% MWCNTs variation with: (c) 1000x magnification and (d) 500x magnification.

## IV. CONCLUSION

This study demonstrated that adding Multi-Walled Carbon Nanotubes (MWCNTs) to the epoxy matrix using acetone solvents improved the mechanical properties of the composite, including its tensile strength and flexibility. The use of acetone reduced the epoxy resin's viscosity, allowing for a better distribution of MWCNTs, and thus enhancing composite reinforcement.

Additionally, increasing the MWCNT concentration from 0.25% to 1% led to a gradual improvement in the mechanical strength, with the maximum increase observed for 1% of the MWCN. The analyses showed that the MWCNT-incorporated composites exhibited a rougher fracture surface, indicating increased resistance to delamination and crack propagation.

Compared to previous studies, the present work's findings align well with enhanced mechanical performance through improved dispersion of MWCNTs in epoxy matrices. The current research further substantiates the aforementioned observations by confirming that precise dispersion techniques, using acetone, significantly enhance composite strength. Similarly, the study demonstrated improvements in tensile properties through optimized Nano filler-matrix interactions, supporting this work's findings regarding the importance of interfacial adhesion and homogeneous dispersion. However, this research's approach extends beyond previous efforts by specifically optimizing filament winding parameters alongside ultra-sonication dispersion technique.

These findings align with previous research which reported a notable tensile strength increase of approximately 28.26% when integrating 1 wt% MWCNT into glass-flax fiber hybrid composites. While their method employed compression molding with prolonged sonication and rotary shaking to enhance dispersion, this study's filament winding approach with acetone solvent presented a more substantial improvement in tensile strength. This suggests that the acetone solvent technique adopted in the current work provides superior dispersion and nanotube-matrix adhesion.

In practical terms, this research contributes to the advancement of composite materials for aerospace applications, potentially improving fuel efficiency and payload capacity. The proposed methodology could serve as a basis for further development of advanced composite materials for industries requiring superior performance.

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