EFFECT OF MULTI-WALLED CARBON NANOTUBES ON THE MECHANICAL AND DYNAMIC BEHAVIOR OF WOVEN CARBON FIBER/EPOXY COMPOSITES

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***ABSTRACT**: Using carbon fiber/epoxy composites with different weight fractions of 0%, 0.1%, 0.2%, 0.3%, and 0.4% of multi-walled carbon nanotubes (MWCNTs) was the subject of this investigation. The composites' uniform three-layer carbon fiber reinforcing structure and epoxy polymer matrix were achieved by a manual lay-up approach. A battery of experiments were executed to assess the dynamic and mechanical capabilities of the created composites. Tensile tests, flexural tests, and impact resistance. In addition, the fracture surfaces and MWCNT dispersion were examined using scanning electron microscopy (SEM). Using 0.328 weight percent of multi-walled carbon nanotubes (MWCNTs) significantly increased the tensile strength (179.72 MPa) and impact resistance (34.383 KJ/m2). Because the nanotubes were evenly distributed throughout the epoxy matrix, stress was better transferred to the fibers and crack formation and propagation were postponed, leading to this improvement. At 0.4 weight percent, the strength kept going up in flexural testing all the way up to 62.312 MPa, which is probably because the matrix stiffened up as the nanocarbon filled micro-voids and reinforced the interfaces between the composite layers. By confirming more uniform nanocarbon distribution and stronger fiber-matrix bonding at these concentrations, scanning electron microscopy (SEM) lent credence to the mechanical trends and highlighted the advantages of employing nanofillers within the ideal dosage and dispersion ranges.*

Mechanical properties of carbon fiber/epoxy composites containing multi-walled carbon nanotubes (MWCNTs) are the subject of this article.

***KEYWORDS**: Carbon fiber/epoxy composites, Multi-walled carbon nanotubes (MWCNTs), Scanning electron microscopy (SEM), Fiber-matrix bonding, Crack propagation*

1 INTRODUCTION

In order to find constructions that are more resistant, lighter, efficient, and cost-effective, engineers typically start by analyzing the costs and performance of materials under realistic and environmental situations. As a vital ingredient in creating intelligent and environmentally friendly composites, carbon nanotubes (CNTs) have attracted a lot of interest in this field. In recent years, composite materials have played an increasingly important role in numerous technical and industrial breakthroughs. In order to create a new material with specialized mechanical properties that fulfill specific engineering criteria, these materials are created by mixing two different components that differ chemically and physically. Epoxy reinforced with multi-walled carbon nanotubes (MWCNTs) is an example of a matrix phase, and carbon nanofiber layers are an example of a reinforcement phase. These two components work together to form composite structures. The aerospace, automotive, aviation, sports equipment, and military industries are just a few of the many modern uses for composite materials. Materials that improve structural rigidity, durability, crashworthiness, and energy absorption during collisions while reducing overall vehicle weight are in great demand in the automobile sector, for instance. Advanced composite replacements to traditional heavy metal alloys and expensive materials can accomplish these goals [1][2].

Sánchez et al. [3] utilized VARIM to make multi-scale carbon fiber/epoxy composites and looked at how amino-functionalized MWCNTs affected their flexural properties. Load transfer and flexural strength were both improved as a result of better interfacial bonding. The research looked at epoxy composites reinforced with amine-functionalized MWCNTs using molecular dynamics simulations [4]. In terms of mechanical behavior and load transfer efficiency, the results demonstrated that convalent bonding played a significant impact. Using carbon nanotubes and nano clay. Salimi et al. [5] studied glass/carbon/epoxy hybrid composites reinforced with amino-MWCNTs and a combination of amino-MWCNTs and Nanoclay. They found that combining both nano-fillers improved flexural strength by 22%, impact strength by 12.2%, and elastic modulus, while amino-MWCNTs alone increased impact strength by 49.9% but slightly reduced tensile strength. SEM analysis showed enhanced interfacial bonding with nano-fillers. Saadatyar et al. [6] investigated the effect of MWCNTs on the mechanical properties of unidirectional carbon fiber-reinforced epoxy (UCFRE) composites. Adding 0.1 phr MWCNT improved transverse tensile strength, modulus, and strain-at-break by 28.5%, 25%, and 14%, respectively. Fracture toughness increased by 39% (transverse) and 9% (longitudinal) at 0.3 phr, while interlaminar and lap shear strengths improved by 8% and 5%. SEM analysis confirmed that these enhancements were due to improved fiber–matrix adhesion and MWCNT toughening effects. Xie et al. [7] modified coal-tar pitch using polyethylene glycol -200 and -400 with p-toluene sulfonic acid as a catalyst to enhance its properties. The modification increased resin content by 52–55 wt.%, carbon yield by 18 wt.%, and improved aromatic condensation. PG-200 modification led to better fibrous structure, higher graphene layer ordering, and increased stack height in the resulting semi-coke. Viscosity changes varied with PEG type, influencing coke microstructure. Hosseini Farrash et al. [8] experimentally investigated the dynamic properties of hybrid composites reinforced with CNTs and microfibers. Various beam and plate specimens were fabricated, and free vibration tests were conducted. CNT addition to glass/epoxy increased the natural frequency by 9.4% and reduced damping by 12.3%, while CNT/carbon/epoxy showed a 13.9% frequency reduction and 31.5% increase in damping. Finite element analysis and SEM supported the findings, emphasizing the role of CNT dispersion and interfacial bonding on dynamic behavior.

Xiao et al. [9] investigated the enhancement of interfacial properties in carbon fiber/epoxy composites by depositing MWCNTs onto T300 carbon fibers. Using an aqueous suspension method, the treated fibers were incorporated into laminated composites via molding. Results showed improved wettability, higher surface energy, and stronger interfacial adhesion. Mechanical testing revealed significant increases in flexural strength (15.1%), tensile strength (17.6%), and interlaminar shear strength (12.6%) compared to untreated composites. The improvements were attributed to better interfacial bonding, reduced porosity, and mechanisms such as interfacial friction and resin toughening. According to this research, composite materials' performance is much improved when CNTs are mixed with reinforcing fiber. Their superior mechanical characteristics render them ideal for cutting-edge engineering uses. CNTs enhance the composite system's strength, durability, and multifunctionality.

2 DESCRIPTIVE

2.1 Supplies

Carbon fiber fabric and epoxy resin were used to create composite panels with dimensions of 30*30 cm. The nano-reinforcement concentrations ranged from 0 to 0.4 weight percent. A homogeneous blend with good flow and wetting properties was produced by using a two-component epoxy system with a low-viscosity ratio of 2:1 (resin to hardener). It was ideal for hand lay-up processing due to its ability to effectively penetrate fiber bundles and its low viscosity (~200 cP at 23 C). The study utilized multi-walled carbon nanotubes (MWCNTs) that were 90% pure, with a length of 10-30μm, an outer diameter of 10-30 nm, and a specific surface area more than 200 m²/g. There was a bulk density of 0.06 g/cm³ and a real density of about 2.1 g/cm³. Because of these qualities, they can be used to reinforce composites that are made of epoxy. Reinforcing carbon fibers were 6.89 ends/cm and 6.89 picks/cm of balanced plain weave fabric with a nominal thickness of 0.15 mm. With Carbon 1K tows running through the fabric's warp and weft directions, it exhibited uniform mechanical behavior along both dimensions.

2.2 Composites manufacturing

A manual lay-up technique was used to fabricate the composite laminates. A 4 mm thick silicone rubber mold was used, and to avoid adhesion after curing, a wax-based release agent was applied to the surfaces of the mold. Woven mats, or three layers of carbon fiber cloth, were the principal reinforcing element of the composite. The volume ratio of the epoxy matrix and its hardener was 2:1, meaning that 50 milliliters of hardener was added for every 100 milliliters of epoxy. Without the use of a dispersion agent, MWCNTs were mixed into the epoxy at different weight fractions.

Rather, a magnetic stirrer was used to achieve dispersion, which mixed the material by heat and shear at the same time. The technique used here guaranteed that the nanofillers were evenly dispersed throughout the resin. Following the lay-up process, the samples were allowed to cure at room temperature while being compressed.

Fig. 1 Sample manufacturing stages

2.3 Mechanical testing and characterization

A battery of tests designed to measure the mechanical and dynamic properties of the produced multiscale carbon fiber/epoxy composites were carried out in compliance with worldwide standards. A SEM was used for morphological analysis in addition to tensile, flexural, impact, and free vibration tests. Every specimen was meticulously measured and subjected to testing in a controlled setting. A WOW-200 universal testing machine, capable of withstanding loads ranging from 0 to 180 KN, was used to conduct tensile testing in accordance with ASTM D3039. The specimens' dimensions were 115 mm in gauge length, 250 mm in length, 25 mm in width, and 3.5 mm in thickness. Two millimeters per minute was the crosshead speed. Strain at break, Young's modulus, and tensile strength were all measured throughout the test. Using the identical apparatus in a three-point bending arrangement, flexural tests were conducted in accordance with ASTM D790 requirements. The measurements of the specimen were 128mm × 12.7mm × 3.5mm, and it had a 56mm support span. The calculation for the crosshead speed, which takes span and specimen thickness into account, is based on the standard. The flexural strength and modulus were calculated using the load-deflection curves that were produced. An example of a compound pendulum, like the centrally situated hand of a clock, was subjected to impact testing in accordance with ISO 179 using a Charpy impact tester with a hammer mass of 2.05 kg. A 55mm×10mm×3.5mm notched specimen was utilized to assess the composite's ability to absorb energy when subjected to a rapid load. A free vibration setup was used to assess the vibration damping behavior in accordance with ASTM E756. A cantilever beam was formed by clamping specimens that were cut to dimensions of 200 mm × 20 mm × 3.5 mm. A high-sensitivity accelerometer captured the vibration signal, and the damping ratio was determined by calculating the decline in amplitude using the logarithmic decrement approach. Lastly, SEM analysis was carried out to examine the morphology of the fracture surfaces and the quality of the MWCNT dispersion in the epoxy matrix. The VEGA3 TESCAN SEM was used to investigate the gold-coated samples, which revealed matrix cracking, fiber pull-out, and distribution or clustering of nanotubes. This was useful for associating the mechanical performance of the various composite groups with their microstructural characteristics.

3 FINDINGS AND ANALYSIS

3.1 Thermomechanical characteristics

3.1.1 Testing for Tensile

Adding CNTs to the carbon fiber/epoxy composite significantly improved its mechanical performance, as seen in the tensile test results. Figure 1's stress-strain curves showed that at a CNT concentration of 0.3 wt%, the tensile modulus recorded 4.57GPa and the tensile strength 179.72MPa. The successful transmission of stress from the matrix to the carbon fibers by means of the scattered CNTs which function as nano-bridges to impede crack propagation and postpone failure is responsible for this enhancement. With this amount of CNTs, the matrix becomes more rigid and the fiber-matrix contact becomes stronger, leading to better stress distribution when subjected to tensile loading. At 0.4 wt% CNT and in the control sample devoid of CNTs, on the other hand, these values decreased, suggesting a performance barrier. Curiously, at 0.4 wt% CNT, the specimen was able to withstand a maximum stress of 15.36 KN, indicating that there was an improvement in load-bearing ability at this concentration, but the tensile efficiency was lowered. Figure 2's bar chart further demonstrated that 0.3 wt% gave the best tensile performance, demonstrating the positive benefits of CNTs up to this point.

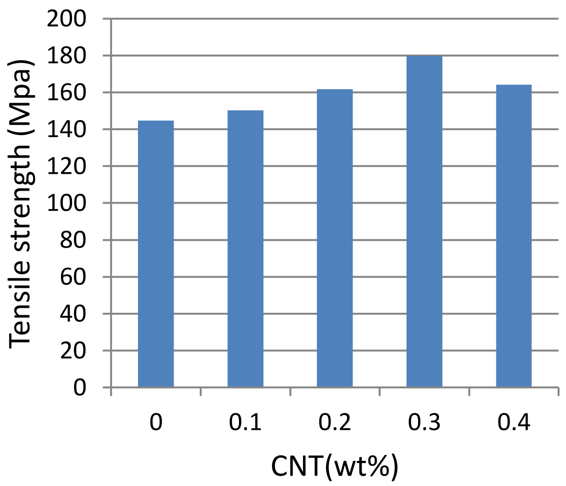

Fig. 2 The effects of CNTs weight fraction on tensile strength

3.1.2 Testing for flexure

The impact of CNTs concentrations on the composite's flexural behavior is shown by the bending test results. The results shows that the flexural stress increased gradually with the addition of CNTs, reaching a maximum of 62.312 MPa at a concentration of 0.4wt% CNTs. The reason for this improvement is that the presence of well-dispersed CNTs increases the stiffness and strengthens the bonding between surfaces, making it more resistant to deformation caused by bending loads. CNTs improve stress distribution at the fiber-matrix interface, which in turn increases flexural strength by bridging microcracks and restricting matrix deformation. At 0.3 wt%, the flexural modulus peaked at 5.074 GPa, and then it slightly decreased as the concentration increased, following a similar pattern. Figure 4's "Flexural Modulus & CNT (wt%)" and Figure 3's "Flexural Stress & CNT (wt%)" bar charts visually corroborated these tendencies, revealing a peak modulus of 0.3wt% and a peak flexural strength of 0.4wt%, respectively. These visuals add credence to the idea that CNTs improve flexural performance, but that their influence varies with concentration and maybe even with the kind of loading used.

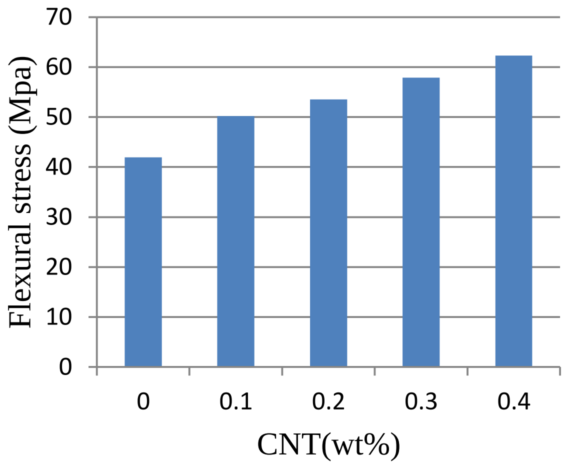

Fig. 3 The effect of CNTs concentrations on flexural modulus

3.1.3 Testing for Impact

Findings from the impact tests provide light on how different CNTs concentrations affect the composite material's energy absorption capabilities under abrupt loading events. The results show that the addition of CNTs significantly improves both the impact energy and the impact strength. Enhanced energy absorption capability was indicated by the impact energy peaking at 1.5 N.m at 0.3 wt% CNT. At 0.3 weight percent CNT, the impact strength which is the energy absorbed per unit area—maximized at 34.38 KJ/m^2, and at 0.4 weight percent CNT, it marginally rose to 20.61 KJ/m^2. The capacity of CNTs to physically deflect, bridge, and slow down the development of cracks following abrupt contact is responsible for this improvement. Nanotubes improve the composite's toughness and fracture resistance by dissipating energy through pull-out and interfacial friction, which they accomplish on a nanoscale. exceeding the amount noted at 0.3wt% (34.383KJ/m^2). Figure 5 of the "Impact Strength (KJ/m^2) & CNT (wt%)" chart clearly confirms these patterns, with the highest bar height corresponding to the 0.3-0.4wt% CNT range. There is a small discrepancy in the reporting and interpretation of "impact energy" and "impact strength," but generally speaking, it appears that adding CNTs makes the material more tough, with an ideal performance window of about 0.3-0.4wt% CNT.

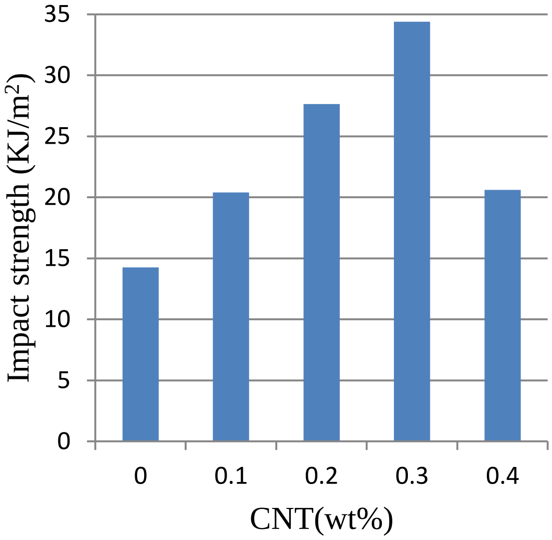

Fig. 4 The effect of CNTs concentrations on impact strength

3.2 Analysis with Scanning Electron Microscopy (SEM)

Using scanning electron microscopy (SEM), we analyzed a subset of composite samples with 0.1wt% and 0.3wt% CNTs to learn more about their microstructural properties and how they dispersed in the epoxy matrix. We picked these two concentrations to see how the dispersion of nanoparticles and fracture morphology changed with low and optimal CNT content.

Micrographs taken using a scanning electron microscope showed that the nanotubes in the 0.1wt% CNT sample were dispersed rather evenly throughout the matrix, with almost little agglomeration, which is indicative of good CNT mixing and integration. There appeared to be minimal CNT pull-out and good matrix adherence on the fracture surface.

The 0.3wt% CNT sample, on the other hand, showed a denser and more linked CNT network, with fiber layer bridging and matrix cracks more apparent. Despite some areas exhibiting clumping of CNTs, the overall dispersion was good. At this concentration, the mechanical performance improved because the higher CNT content improved crack deflection and energy absorption processes.

Further proof of the reinforcing role of CNTs at ideal loading levels is provided by these microstructural data, which support the results of the tensile and flexural tests.

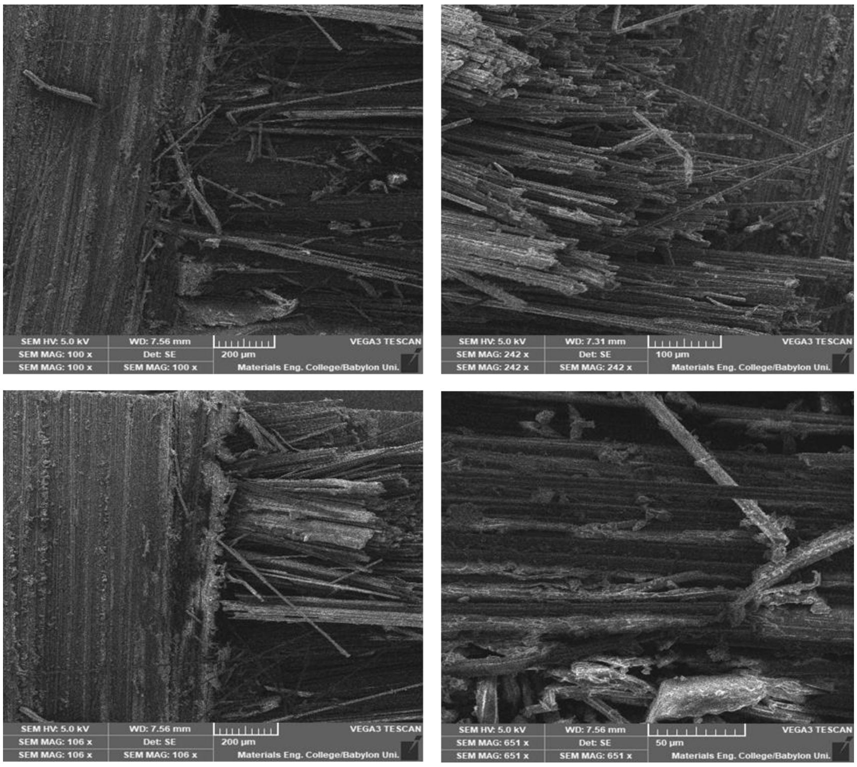

Fig. 5 SEM Micrograph of 0.1wt% CNT

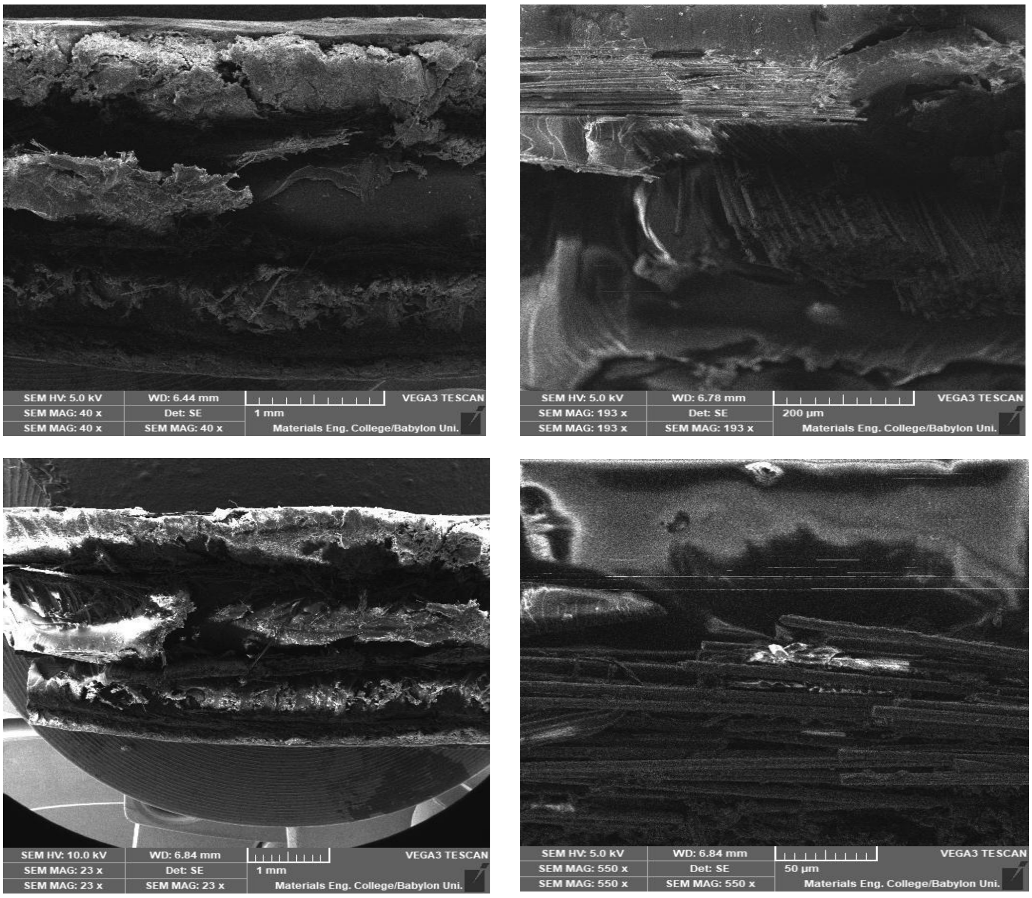

Fig. 6 SEM Micrograph of 0.3wt% CNT

4 CONCLUSIONS

Numerous mechanical and dynamic properties of woven carbon fiber/epoxy composites were significantly enhanced by the inclusion of multi-walled MWCNTs. These enhancements can be summarized as follows:

1. In the tensile test, both tensile strength (179.72MPa) and Young's modulus (4.57GPa) peaked at 0.3wt% CNT, indicating improved stiffness and load transfer; despite the higher load at 0.4wt%, the strength dropped due to CNT agglomeration.
2. The flexural performance also reached its maximum at 0.3wt% (57.89MPa and 5.07GPa), while a slight decline at 0.4wt% confirmed the dispersion limit beyond the optimal concentration.
3. Impact strength increased with CNT content, peaking 33.73KJ/m^2 at 0.4wt%, but 0.3wt% still offered a better balance between toughness and structural integrity.
4. SEM observations supported the mechanical data, showing uniform CNT dispersion at 0.1wt%, and a denser CNT network with better crack bridging and fracture resistance at 0.3wt% despite minor clustering.
5. Overall, the incorporation of 0.3wt% MWCNTs resulted in the best compromise between reinforcement and dispersion, making it a practical choice for structural applications requiring strength, rigidity, and energy absorption.

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