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Experimental tensile test and micro-mechanic investigation on carbon nanotube reinforced carbon fiber composite beams

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Abstract. Carbon nanotubes (CNTs) have received increased interest in reinforcing research for polymer matrix composites due to their exceptional mechanical characteristics. Its high surface area/volume ratio and aspect ratio enable polymer-based composites to make the most of its features. This study focuses on the experimental tensile testing and fabrication of carbon nanotube reinforced composite (CNTRC) beams, exploring various micromechanical models. By examining the performance of these models alongside experimental results, the research aims to better understand and optimize the mechanical properties of CNTRC materials. Tensile properties of neat epoxy and 0.3%; 0.4% and 0.5% by CNT reinforced laminated single layer (0°/90°) carbon fiber composite beams were investigated. The composite plates were produced in accordance with ASTM D7264 standard. The tensile test was performed in order to see the mechanical properties of the composite beams. The results showed that the optimum amount of CNT was 0.3% based on the tensile capacity. The capacity was significantly reduced when 0.4% CNT was utilized. Moreover, the experimental results are compared with Finite Element Models using ABAQUS. Hashin Failure Criteria was utilized to predict the tensile capacity. Good conformance was observed between experimental and numerical models. More importantly is that Young' Moduli of the specimens is compared with the prediction Halpin-Tsai and Mixture-Rule. Although Halpin-Tsai can accurately predict the Young's Moduli of the specimens, the accuracy of Mixture-Rule was significantly low.

Keywords: carbon fiber fabric; carbon nanotube; carbon nanotube reinforced composites; micro-mechanic models; tensile test

1. Introduction

The advantages of composite materials can be counted as lightness, flexibility, easy transformation into different forms, high fatigue ability, impact and corrosion resistance, resistance to moisture, easy transport, long-term preservation, stable dimensions, easy processing, and ease of recycling (Reddy 2004, Özütok and Madenci 2013, 2017, 2020, Ozutok *et al*. 2014, Asyraf *et al*. 2023, Syamsir *et al*. 2023). In addition to its advantages, there are also some disadvantages that narrow the usage area of composite materials (Vedernikov *et al*. 2020). The most important of the disadvantages is the high cost of producing composites. On the other hand, the fact that composites are not natural products and the raw material is expensive makes it more difficult to repair damaged composite structures. The main material that makes up the composite is the matrix. Since they will transmit the load on the matrices to the fiber, the bond to be established between them is very important, so the properties and type of the adhesive to be used are of great importance (Madenci *et al*. 2020). Adhesives are materials that improve mechanical properties by solidifying when applied to surfaces by adding additives. The mechanical properties they will improve may vary depending on the type of adhesive and application environment.

Interlayer delamination, also known as interface failure and its spreading, happens as a result of the laminated composite materials' decreasing mechanical characteristics, this is a significant drawback of composite laminates. Composite materials must be strengthened and made tougher in order to replace aluminum as the material of choice for structural sections. Due to their better mechanical capabilities in comparison to other materials, nanoparticles make for particularly promising reinforcing materials in this situation. The technology that has emerged to meet the increasing needs of human beings continues to develop day by day. Nanotechnology is a technological development that has emerged with the aim of improving material properties by reducing the size (Ahmad *et al*. 2022a, b, c, Allehyani *et al*. 2022). Particles, thin films and tubes obtained in nano size have offered a wide area of use in technology due to their physical and mechanical properties. The main purpose is to obtain more advantageous structures by working on the micro dimension. Composite materials have enhanced physical characteristics and are now being developed as the main load-bearing components in intricate designs. The usage of the intricate form is complicated by the material's fragility in the curved area. Carbon nanotubes (CNTs), which are nanoscale structured materials consisting of pure

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carbon, can be used to improve these curved sections of a structure. The CNTs have become utilized in many essential fields including engineering and have received attentions amid scientists (Marani and Perri 2017, Farazin and Mohammadimehr 2020, Heidari *et al*. 2020, Ali *et al*. 2021, Madenci 2021, Madenci *et al*. 2023a, b). The application of CNT reinforcement structures in many industries is rising due to their excellent properties such as high strength, low weight, resistance to fatigue and are useable in continuous yarns. Carbon nanotube reinforced composites (CNTRCs) are a cutting-edge category of composite materials that are strengthened by the addition of carbon nanotubes (CNTs). This type of composite material is notable for its exceptional mechanical properties, which are characterized by a ratio of the two in-plane Young's modulus that exceeds 40, meaning that it is highly resistant to deformation under stress. Moreover, the in-plane shear modulus of CNTRCs is exceptionally small compared to the longitudinal Young's modulus, which means that it is highly resistant to shear forces. (Shen *et al*. 2020). Therefore, the auxiliary CNTRC laminate is expected and the magnitude of the Poisson ratio can be increased in some directions. By incorporating carbon nanotubes into the matrix material, CNTRCs can offer several advantages over traditional composite materials. For example, CNTs can improve the strength and stiffness of the composite, making it highly resistant to bending and other types of deformation. Additionally, CNTs can improve the thermal and electrical conductivity of the composite, making it suitable for a wide range of applications, such as in the aerospace, automotive, and electronics industries.

The CNTs are single-walled (SWCNT), double-walled (DWCNT) and multi-walled (MWCNT) which is synthesized by different techniques (with and Fiber-Reinforced Polymer Bars 2007, Wu *et al*. 2018, Asghar *et al*. 2020, Farazin and Mohammadimehr 2020). Carbon nanotubes (CNTs) are known for their high specific surface area, which makes them attractive for use in composite materials because they provide a large surface for stress transfer. However, this same property can lead to strong attractive forces between CNTs, which can cause agglomeration and the formation of stress concentrations that can ultimately lead to failure of the composite material. Fortunately, MWCNTs have a lower specific surface area compared to SWCNTs, due to their larger diameter and multiple graphene walls. This lower specific surface area of MWCNTs, which is typically around 200 m2/g or less, means that they exhibit better dispersibility and are less prone to agglomeration, reducing the formation of stress concentrations. By using MWCNTs instead of SWNTs in composite materials, it is possible to create a more stable and reliable product that is less prone to failure. This is especially important in applications where the composite material will be subjected to high stress or other extreme conditions. The improved dispersibility of MWCNTs also allows for more consistent and homogeneous distribution within the composite matrix, leading to improved mechanical and physical properties. (Rahman *et al*. 2012).

Nanocomposites are materials consisting of nanometer-sized particles dispersed in the matrix. Polymeric nanocomposites are materials that behave like a single phase. It generally contains 1-3% nanoparticles. The macro-scale and micro-scale properties of the same material vary. CNTs have been used in various studies due to their high mechanical properties. Rahman *et al*. (2012) produced composite sheets by hand lay-up method and press using MWCNT-doped epoxy matrix glass fiber at the ratios between 0.1-0.4 wt%. According to the results of the crushing and dynamic mechanical analysis (DMA, Dynamic Mechanic Analysis) tests, the most appropriate weight ratio was 0.3%, They observed an increase of 37%, 21% and 21% for yield strength, modulus of elasticity and tensile, respectively. Gojny, Wichmann *et al*. (2005) investigated the mechanical properties of different CNT types and epoxy matrix composites formed by adding CNT to the matrix at different rates. SWCNT, DWCNT and MWCNT, composite sheets were produced by adding 0.1%, 0.3% and 0.5% of the polymer by weight. The modulus of elasticity, yield strength and impact strength of the produced composite sheets were measured. According to the results of the measurements, it was observed that all mechanical properties increased by 0.5% at most in the DWCNT added plate. Siddiqui, Sham *et al*. (2009) coated the surfaces of glass fibers with CNT-doped epoxy in order to improve the mechanical properties of the material by filling the capillary and brittle cracks of the glass fibers. They produced by using 0.3% CNT added epoxy matrix on the fiber surfaces. In the tests they carried out on various fiber lengths from the produced samples, they saw that the tensile strength and tension were better distributed between the fibers, resulting in a significant increase. Unlike other studies, Zou *et al*. (2004) investigated the mechanical properties of High Density Polyethylene nanocomposite with MWCNTs. They used a mixture of SiO2 and MWCNTs to improve their mechanical properties. As a result of the tests, they saw that a 1% mixture had a positive effect on the composites.

CNTs can be used as functional or structural composite reinforcements, depending on their electrical and thermal conductivity and coefficient, tensile strength, and fracture resistance. Despite having outstanding mechanical characteristics, most studies' measurements of these qualities fall short of expectations. This is a result of the aggregated CNTs' uneven distribution and the inadequate adherence of the CNTs to the polymer matrix.

CNT reinforced composite (CNTRC) laminated materials hold significant promise for diverse applications in various sectors, including mechanical, civil, and aerospace engineering. These cutting-edge materials have the potential to be employed as load-bearing components for a wide range of structures, such as ships, buildings, and aircraft. Over the past several decades, nanotechnology and nanoscience have emerged as captivating fields of research, attracting considerable attention and resources to explore their potential in advancing these innovative materials for industrial and engineering purposes. (Taraghi *et al*. 2014, Chavan and Lal 2017, Lei and Zhang 2018). In conventional approaches, nanotubes are typically dispersed either uniformly or randomly within a material. As a result, the enhancement of their unique mechanical properties might not be fully optimized. This non-ideal distribution can limit the potential benefits that could be derived from the incorporation of nanotubes, and may leave room for further improvement in their performance and utility. (Qin *et al.* 2020). According to the researches on the characterization of nanocomposites, the elastic properties of the material can change according to the production method. Research has demonstrated that incorporating even minor weight fractions of CNTs into polymers can lead to considerable enhancements in mechanical strength, as well as thermal and electrical conductivity. In order to assess the stiffness and strength of CNT reinforced components, a combination of established and modified theoretical approaches and experimental techniques are employed. These methods enable a more comprehensive understanding of the material properties, helping to maximize the potential benefits of integrating CNTs into various applications. In most theoretical analyses, the strength and stiffness properties tend to increase as the weight fractions of CNT increase. However, experimental studies reveal significantly different types of behavior. For a given CNT weight fraction limit, the strength and hardness properties continue to increase and then decrease. The constituent elements of a composite material, including fibers and the matrix, play a crucial role in determining the composite's behavior during loading, damage progression, failure mechanisms, and overall strength. Numerous studies in the literature have explored the characterization of polymer composites reinforced with various types of fibers, such as glass, carbon, Kevlar, and natural fibers. Understanding the specific properties and interactions of these components is essential in optimizing the performance of composite materials for a wide range of applications. (Valença *et al.* 2015).

In recent years, numerous studies have been conducted by researchers to explore composite and CNTRC materials and their properties. Some notable examples include: Petrone and Meruane (2017) examined the mechanical properties of a composite panel consisting of unidirectional flax fibers embedded within a polyethylene matrix. This study aimed to understand how the integration of flax fibers influenced the composite's performance. Bandaru *et al.* (2016) examined the mechanical behavior of thermoplastic composites reinforced using homogenous, two-dimensional plain weave textiles comprised of Kevlar and basalt fibers. They created five different composite laminates for their investigation utilizing compression molding and poly-propylene resin. They performed static tensile and in-plane compression tests on these laminates to assess their mechanical characteristics. Biercuk *et al.* (2002) explored the enhancement of thermal and mechanical properties of SWCNT epoxy composites without the need for chemical functionalization of the carbon nanotubes. By incorporating SWCNTs, they were able to increase the thermal transport properties of industrial epoxy, leading to improved performance.

In this study, both experimental tensile testing and theoretical micromechanical models were employed to investigate the mechanical properties of CNTRC beams. Alongside experimental testing, the mixture-rule and Halpin-Tsai models were utilized for calculations. The elastic properties of the composite were determined using a universal testing machine to conduct uniaxial tensile tests. Samples were prepared from MWCNT reinforced composites with varying weight fractions of MWCNT. The study encompassed pure epoxy as well as 0.3%, 0.4%, and 0.5% weight CNT reinforced carbon fiber composite samples. To ensure the repeatability and accuracy of the results, three samples were prepared for each weight fraction according to the ASTM standard (D3039/3039M). Uniaxial tensile testing was performed on these samples, and the corresponding values were averaged to obtain the final value for each set.

Table 1 Material properties of Epoxy

Tensile Strenght (MPa)	Young's Moduli (kPa)	Elongation at break (%)	Density (g/cm^3)
70-80	3-3.3	5-6.5	1.18-1.20

Table 2 Mechanical properties of CNTs

Tensile Strenght (GPa)	Young's Moduli (TPa)	Elongation at break (%)	Density (g/cm^3)
10-60	1	1.3-2	10

Table 3 Mechanical properties of Carbon fiber fabric

Tensile Strenght (MPa)	Young's Moduli (GPa)	Elongation at break (%)	Density (g/cm^3)
3950	238	1.7	1.76

2. Materials and processing of CNT reinforced composite

In this work, the composites were made using an industrial vacuum bagging technique. In this method, layers that have been resin-impregnated are compressed to ensure homogeneous consolidation. This method calls for the use of carbon fabric, epoxy resin, a vacuum pump, peel ply, sealing tape, bagging films, and infusion mesh as well as other supplies. The epoxy resin used in this study has a viscosity of 600-900 mPas and is a two-phase mixture, comprising 80-90% diglycidyl ether bisphenol A and 10-20% aliphatic diglycidyl ether. The mechanical properties of this epoxy resin, according to the DIN WL 5.3203-11:1978-11 standard, are presented in Table 1. MWCNTs were chosen for this study due to their cost-effectiveness and homogeneous dispersibility in epoxy resins compared to single-walled carbon nanotubes. The mechanical properties of MWCNTs, with diameters ranging from 5-50 nm and lengths between 10-30 µm, can be found in Table 2. This study made use of a 200g carbon fiber cloth made from plain weave Tenax-E HTA 40 yarn. When strength, low weight, and carbon content are crucial considerations, CFRP works effectively. Table 3 provides more information on the carbon fiber fabric's mechanical characteristics.

The fabrication process for the composite material can be broken down into the following steps:

The desired volume fraction of MWCNT is dispersed in

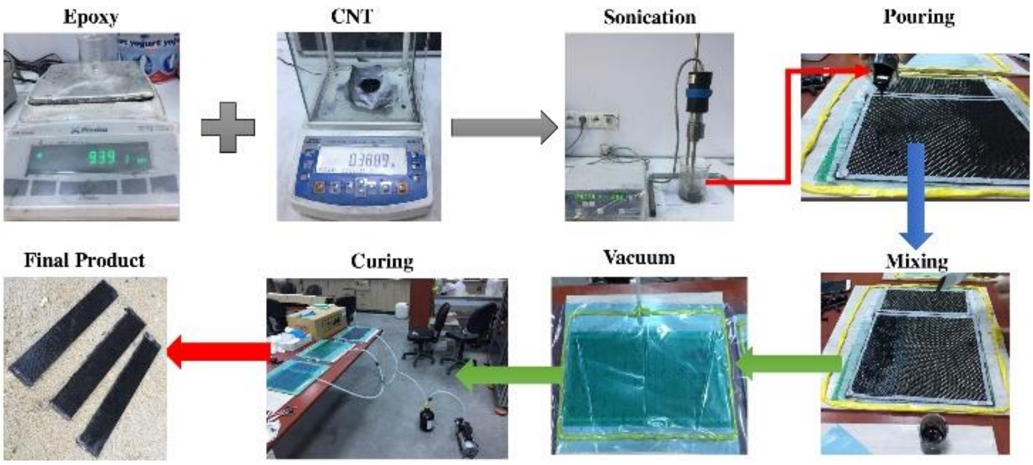

Fig. 1 CNTRC specimen manufacture

acetone to ensure proper mixing and prevent agglomeration.

The mixture of MWCNT and acetone undergoes a sonication process for 30 minutes to deagglomerate the MWCNTs.

The MWCNT/acetone mixture is then combined with pre-weighed, heated epoxy (80°C) to maintain adequate fluidity and ensure a void-free mixture.

The epoxy/MWCNT/acetone mixture is stirred for 15 minutes at 80°C to ensure thorough mixing.

A second sonication process, lasting 3 hours, is conducted to further deagglomerate the MWCNTs within the epoxy, ensuring that the acetone is removed.

The MWCNT/epoxy mixture is placed under vacuum to eliminate any air bubbles that may have been trapped during the stirring and sonication processes.

The hardener is added to the MWCNT/epoxy mixture and stirred by hand to guarantee proper mixing of the components.

The final mixture (MWCNT/epoxy/hardener) is poured into a wooden mold and allowed to cure at atmospheric conditions for two days.

This process is repeated for each desired weight fraction of MWCNT in order to create composite samples with varying properties.

3. Micro-mechanical models for effective material properties of CNTRC

In order to quickly and independently determine the mean elastic modulus and strain in heterogeneous materials, analytical and computational homogenization approaches are useful tools. The creation of reliable micromechanical models for the modeling and operation of carbon nanotubes may open the door to a greater knowledge and, consequently, a more widespread use of this class of composites, as well as increased performance.

3.1 Rule of mixture model procedure

According to the rule of mixture by introducing the CNT efficiency parameters (η_1, η_2, η_3), the effective Young's modulus and shear modulus of the matrix of CNTRC layer can be expressed as

$$E_{11}^{M} = \eta_1 E_{11}^{CNT} V_{CNT} + E^{P} V_{P} \tag{1}$$

$$\frac{\eta_2}{E_{22}^{M}} = \frac{V_{CNT}}{E_{22}^{CNT}} + \frac{V_P}{E^P} \tag{2}$$

$$\frac{\eta_3}{G_{12}^{M}} = \frac{V_{CNT}}{G_{12}^{CNT}} + \frac{V_P}{G^P} \tag{3}$$

$$\upsilon_{12}^{M} = V_{CNT} \upsilon_{12}^{CNT} + V_P \upsilon^{P} \tag{4}$$

$$\rho^{M} = V_{CNT} \rho^{CNT} + V_P \rho^{P} \tag{5}$$

where E_{11}^{CNT}, E_{22}^{CNT} and G_{12}^{CNT} indicate the Young's moduli and shear modulus of SWCNTs, respectively, and E^P and G^P represent the properties of the polymer. The V_{CNT} and V_P are the volume fractions of the carbon nanotubes and polymer, respectively, and are related by

$$V_{CNT} + V_P = 1 \tag{6}$$

The volume fraction of CNTs "V_{CNT}" for uniform distribution in CNTRC beam, which can be obtained from the following equation

$$V_{CNT} = \frac{W_{CNT}}{W_{CNT} + \left(\frac{\rho^{CNT}}{\rho^{P}}\right)(1 - W_{CNT})} \tag{7}$$

where W_{CNT} is the mass fraction of the CNT in the nano-composite.

The mixture is rule developed for mechanical properties of fiber and matrix as

$$E_{11} = E_{11}^{Fiber} V_{Fiber} + E_{11}^{M} V_{M} \tag{8}$$

$$\frac{1}{G_{12}} = \frac{V_{Fiber}}{G_{12}^{Fiber}} + \frac{V_M}{G_{12}^{M}} \tag{9}$$

$$\rho = \rho_{Fiber} V_{Fiber} + \rho_M V_M \tag{10}$$

$$\upsilon_{12} = \upsilon^{Fiber} V_{Fiber} + \upsilon^{M} V_M \tag{11}$$

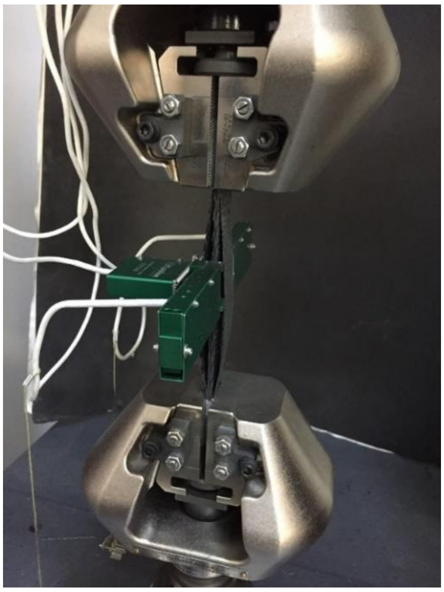

Fig. 2 Test setup

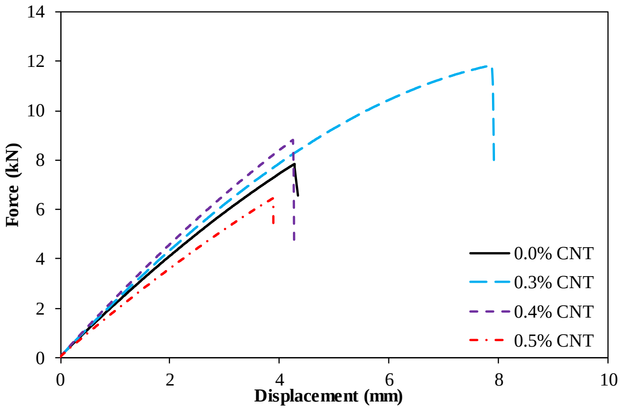

Fig. 3 Test setup

3.2 Halpin-Tsai model procedure

The modulus of the elasticity of the short FRP composite structure is computed using Halpin–Tsai relationship and conceded as

$$\begin{aligned} E_{11}^{M} = {} & \frac{3}{8}\left[1+2\left\{\frac{l}{d}\right\}\left\{\frac{\frac{E_{11}^{CNT}}{E^{P}}-\left(\frac{d}{4t}\right)}{\frac{E_{11}^{CNT}}{E^{P}}+\left(\frac{l}{2t}\right)}\right\}V_{CNT}\right]* \\ & \left[1-\left\{\left(\frac{\frac{E_{11}^{CNT}}{E^{P}}-\left(\frac{d}{4t}\right)}{\frac{E_{11}^{CNT}}{E^{P}}-\left(\frac{d}{2t}\right)}\right)V_{CNT}\right\}E^{P}\right]+ \\ & \frac{5}{8}\left[1+2\left\{\frac{\frac{E_{11}^{CNT}}{E^{P}}-\left(\frac{d}{4t}\right)}{\frac{E_{11}^{CNT}}{E^{P}}+\left(\frac{l}{2t}\right)}\right\}V_{CNT}\right]* \\ & \left[1-\left[\left\{\frac{\frac{E_{11}^{CNT}}{E^{P}}-\left(\frac{d}{4t}\right)}{\frac{E_{11}^{CNT}}{E^{P}}+\left(\frac{d}{2t}\right)}\right\}V_{CNT}\right]^{-1}E^{P}\right] \end{aligned} \tag{12}$$

where “*l*, *d* and *t*” length, outer diameter and the thickness of CNT, respectively.

Table 4 Hashin Failure Criteria

Mode description	Equations
Tensile fiber mode	$F_f^t=\left(\frac{\sigma_{11}}{X^T}\right)^2+\left(\frac{\tau_{12}}{S^L}\right)^2$
Fiber compressive mode	$F_f^c=\left(\frac{\sigma_{11}}{X^C}\right)^2$
Tensile matrix mode	$F_m^t=\left(\frac{\sigma_{22}}{Y^T}\right)^2+\left(\frac{\tau_{12}}{S^L}\right)^2$
Compressive Matrix mode	$F_m^c=\left(\frac{\sigma_{22}}{2S^T}\right)^2+\left[\left(\frac{Y^C}{2S^T}\right)^2-1\right]\frac{\sigma_{22}}{Y^C}+\left(\frac{\tau_{12}}{S^L}\right)^2$

4. Experimental study

Tensile tests were performed utilizing a universal testing machine to assess the mechanical characteristics of the CFRP composite during the experimental phase of the project. These characteristics include elastic modulus and ultimate strength. The specimens were prepared and analyzed in accordance with ASTM D638 criteria to guarantee standard testing and reliable findings. 12 specimens with three repetition were tested. The specimens have different CNT ratio including 0%, 0.3%, 0.4% and 0.5%. The nominal dimensions of the experimented specimens were 250×25×0.6 mm (length×width×thickness). The distances between the claws were 190 mm. The test setup is depicted in Fig. 2. An extensometer was also used in the experiments.

5. Numerical study

To validate the experimental results, numerical analyses were conducted using the finite element software, ABAQUS. The composite coupons were modeled using S4R four-noded shell elements. Appropriate boundary conditions were applied to the ends of the coupons. The elastic properties of the composites were defined using the “Lamina” type, and the Hashin failure criteria were specified to simulate the failure of the composite material. This failure criteria is already implemented in ABAQUS and has been successfully employed by numerous researchers to simulate the behavior of fiber-reinforced polymer (FRP) composites in reinforced concrete structures.

The Hashin failure criteria (Hashin and Rotem 1973, Hashin 1980) define four failure modes: tensile fiber mode, fiber compressive mode, tensile matrix mode, and compressive matrix mode. The equations for computing these failure modes can be found in Table 7. By applying these failure criteria, the numerical analysis can accurately predict the composite’s behavior, thereby corroborating the experimental findings.

6. Results and discussion

The average load-displacement curves of the specimens are depicted in Fig. 3. It is seen that using CNT may have both negative and positive effects depending on the usage

Fig. 4 Tested specimens

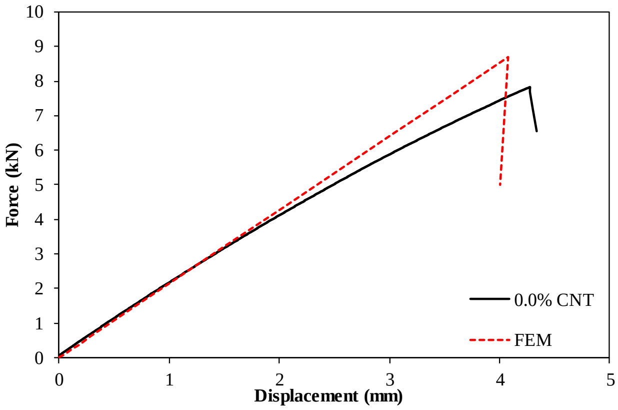

Fig. 5 Comparision of the numerical and experimental result

ratio of CNT. The results revealed that using 0.3% and 0.4% CNT increased the tensile capacity of the specimens. 51% and 12% increases in the tensile capacities for the specimens having 0.3% and 0.4% CNT compared to the reference specimen were observed. On the other hand, when 0.5% CNT was utilized, it was observed that the tensile capacity drastically decreased. 18% decrease in the tensile capacity was detected for the specimens with 0.5% CNT compared to the reference specimen.

Fig. 4 depicts the failure modes of the specimens. The all specimens experienced sudden and brittle failure. Matrix crack sounds were emerged around 30% of load capacity as initial damage. As the loading continues, delimination damage was observed in the longitudinal direction. Final damage, i.e., failure, occurred due to fiber breakage.

Table 5 Micro-mechanical model results

	Young’s Moduli (GPa)		
Sample	Experimental	Halpin-Tsai	Mixture-Rule
0.0%wt CNT	12.18	11.48	22.34
0.3%wt CNT	13.42	13.18	24.52
0.4%wt CNT	13.87	11.51	21.08
0.5%wt CNT	10.29	10.02	19.25

Numerical analyses were utilized to verify the experimental result of the reference specimen. It is seen that initial stiffness of the experimental and numerical results are almost same (Fig. 5). As the loading increases the numerical models behave more rigidly than the experimented specimen. The reason for this can be attributed to micro cracks which were not included in the numerical models. These behaviors resulted in slightly decrease in the load carrying capacity for the experimented specimen. 10% difference in the tensile capacity was detected. It can be said that a good confarmance was obtained between the numerical and experimental findings.

The material properties of the samples, obtained using micromechanical models, were determined analytically. The results of this analysis are presented in Table 5, alongside the experimental results, allowing for a direct comparison between the two sets of data. This approach enables a comprehensive evaluation of the accuracy and reliability of the micromechanical models in predicting the properties of the composite materials.

The results of Young’s Moduli determined by micro-mechanic models revelaed that Halphin-Tsai give more accurate results than that of Mixture rule. 6% difference is observed between experimental results and Halpin-Tsai while this ratio modifies to 83% for the samples without CNT. On the other hand, when CNT is 0.3% these ratios modify to 2% and 83% for Halpin-Tsai and Mixture-Rule, respectively. Furthermore, when CNT is 0.5% these ratios modify to 3% and 87% for Halpin-Tsai and Mixture-Rule, respectively. It is seen that the accuracy of Mixture-Rule is significantly low.

7. Conclusions

In this study, four different percent of CNT specimens were firstly manufactured and the steps of production are explained. Later, these specimens were tested under tensile load. Young’s Moduli and tensile laod-displacement curves of the specimens are reported. The results are compared with the numerical models using Hashin Failure Criteria. Moreover, two different micro-mechanical models including Halpin-Tsai and Mixture Rule are utilized to predict Young’s Moduli of the specimens.

- The experimental results revealed that tensile capacity of the specimens using 0.3% and 0.4% CNT increased capacity by 51% and 12%, respectively.
- Tensile capacity of the specimen using 0.5% CNT decreased capacity by 18%.
- Using Hashin Failure Criteria accurately predicted the

experimental results in terms of tensile capacity and displacement.

- Halpin-Tsai accurately estimated the Young’s Moduli of the specimens with maximum of 6% difference. On the other hand, Mixture-Rule predicted the Young’s Moduli with minimum 83% accuracy.

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