Enhancing Toughness of Fiber Reinforced Plastic Composites using Nano-Materials

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Abstract

The exceptional properties of carbon nanotubes render them potential candidates to enhance the mechanical properties of fiber reinforced composites. The current state of research suggests mixed results in terms of the enhancement that can be achieved and further research is warranted. In this research, a wide range of carbon nanotubes (CNT) volume fraction was examined between 0 and 2% on an epoxy resin carbon reinforced composite. Tensile tests were performed to measure the elastic modulus and toughness of the material. Experimental results illustrate that toughness of the material was improved by more than 100% and elastic modulus by 28% upon adding 1% CNT. Increasing the added CNT percentage by more than 1% resulted in a decrease in strength and toughness. An optimum percentage of CNT that maximizes the mechanical properties of the composite structure can be determined.

Keywords
Composites, Nanomaterials, Mechanical Testing and Toughness.

1. Introduction
The high strength to weight ratio of fiber reinforced plastic (FRP) composite materials makes them potential candidates in a wide range of applications. Industries view them as sustainable alternatives to replace some of the materials currently used to manufacture their products. FRPs, in general, offer unique advantages as they combine the properties of the fiber and the polymeric matrix, featuring the benefits of both materials and offering capability to tailor material properties. The strength of the fiber together with the ductility of the polymer creates a lightweight composite with superior properties (Callister and Rethwisch 2018). To enhance the mechanical properties of composites, additions of nanofillers was considered by researchers. The properties and characteristics of carbon nanotubes (CNT), in particular, provide great prospects to improve the properties of composites. CNTs possess outstanding mechanical properties that highlight them as potential candidates for composite reinforcement. With strength "a hundred times the strength of steel at one sixth of the weight" (Kelsall et al. 2005) and a Young's modulus varying between 1-5 TPa, ductility from 20% to 30%, which correlate to a tensile strength of well above 100 GPa and thermal stability as high as 2800 ^{0}C (Cwirzen et al. 2009). Mixed results are found in the literature regarding the effect of enhancing mechanical properties by adding CNTs to composites. These mixed results could be attributed to many factors including the percentage of CNTs added.

1.1 Objectives
In this research a wider range of CNT percentage will be investigated to determine its effect on composite's toughness. CNT % will be varied from 0-2 %. Mechanical behavior of the material will be tested using uniaxial tension test. Material toughness will be computed using captured stress-strain curves.

2. Literature Review

Koysin et al. (2010) reviewed the effect of continuous fiber reinforced composites modified with nanotubes or nanofibers on the mechanical properties. The nanofibers were either dispersed in the resin or grown on microfibers. The authors reviewed multiple tests conducted by different researchers. The conducted tests were in-plane uniaxial tensile test, compression test, flexural strength, interlaminar shear strength, mode I and II interlaminar fracture toughness, hardness index, impact resistance, fatigue, coefficient of thermal expansion, glass transition temperature, and thermal and electrical conductivities. For the tensile tests, the authors found discrepancies in the published results due to variations in plate thicknesses. Overall, the published results show between 20% and 30% of improvement in the tensile strength in the transverse direction of the glass fibers. From the compression tests, the results also show that the compressive strength of hybrid carbon fiber reinforced plastic's (CFRP)with 5-10 wt. and carbon nano-fiber (CNF) to resin ratio or 10-50 CNT length to diameter ratio increased up to 15%. The stiffness has also increased up to 7%. As for the flexural tests, the flexural stiffness increased by 30% at 5 wt.% CNF whereas it degrades as the weight ratio increases up to 10% and 20%. The addition of CNF has showed an increase of 424% compared with the base composite. The interlaminar shear strength (ILSS) has significantly increased in hybrid composites. As for modes I fracture toughness, at 0.3 % wt CNTs, the fracture toughness has increased by 13%-33%. The mode I fracture toughness showed a drop when the CNT is used as a sizing in the hybrid composite. As for mode II fracture toughness, it was reported that the addition of 7.5% CNFs or 2wt% of CNTs showed significant improvement in mode II fracture toughness. The hardness index showed an improvement of 15% which was consistent throughout the publications (Koysin et al. 2010).

Greef et al. (2011) investigated the effect of adding carbon nanotubes (CNTs) on the damage evolution in a woven carbon fiber/epoxy composite under quasi static tensile loading. The composite studied had 0.25 wt. % of CNT and was produced by using resin transfer molding. Results showed no significant improvement in the Young's modulus and tensile strength but from the acoustic emission measurements, the damage thresholds were improved, the number of medium energy events decreased, and the number of low energy events increased. Godara et al. (2009) studied the effect of dispersing CNTs in an epoxy matrix that was reinforced with carbon fibers. The thermal coefficient of thermal expansion (CTE) does not experience significant changes for the Multi-walled CNTs (MWCNT). The CTE is much lower for the composite without CNTs and much lower than non-functionalized MWCNTs. Upon the addition of CNTs, there was a strong improvement in the crack initiation and propagation energy. The crack initiation energy increased by 75% via modifying the MWCNTs epoxy with a compatibilizer. Similar to the work of Greef et al. (2011), the Young's modulus and tensile strength do not significantly change when comparing CNT surfaces. Han et al. (2020) studied the effect of adding MWCNTs to open-hole carbon fiber-reinforced composite laminates by subjecting the specimen to tensile damage. Two specimens were compared against each other, where specimen A contained the polymer matrix and the carbon fiber, while specimen B included the polymer matrix, carbon fiber and MWCNTs. From the tensile test, the average failure loads of specimens A and B were 47.96kN and 49.79kN, respectively, and the tensile strengths were reported to be 515.70 and 535.38 MPa, respectively. The acoustic emissions (AE) reported from the tensile tests are used to characterize the damage evolution in both specimens. The AE signals reported were concentrated in three areas: matrix cracking, fiber pull-out, delamination and fiber breakage. The frequency range of the three areas are 23-74kHz, 82-120kHz and 120-190 kHz, respectively. The AE signals reported from specimen A were larger than that of specimen B which concludes that the degree of damage in specimen A is more serious than that of B. In addition, specimen B strain field increment is relatively small to the same applied stress concentration when compared to specimen A. The same authors concluded that a certain amount of MWCNTs can thus increase the laminate strength, and the addition of MWCNTs reduces the stress concentration and enhances the strength and fracture interface of the laminate specimens.

Other researches reveal significant advancement in mechanical properties. Gojny et al. (2004) produced nanocomposites with a double-wall carbon nanotube (DWCNTs) and an epoxy matrix and analyzed its mechanical properties by increasing the weight ratio of carbon nanotubes. The CNTs were compared to carbon black filled epoxy and the results show that the addition of 0.1wt% of carbon nanotubes increases the tensile strength and Young's modulus. The fracture toughness and weight ratio of carbon nanotubes are proportional to each other. Moumen et al. (2017) studied the elastic mechanical properties of carbon nanotube reinforced polymers through the aid of instrumented indentation tests. The study was carried out both numerically and experimentally. The materials used for the fabrication of the specimen were an epoxy matrix, carbon fibers fabric, and multi-walled randomly displaced carbon nanotubes. MWCNTs with diameters of 10 nm to 1.5 micrometer, on average, were used. The weight fractions of the carbon nanotubes used were different in which 0, 0.5, 1, and 4% of CNTs were used. Experimental results show that both the interfacial and the composite rigidity portray an increase when the amounts of carbon nanotubes are increased. It was evident that by adding 1% weight fraction of the MWCNTs, the interfacial resistance is increased which in turn increased the modulus of elasticity. In addition, the rigidity increased by 3.5 % through the addition of 1% of the MWCNTs.

Aghamohammadi et al. (2020) investigated the effect of multi-walled carbon nanotubes on metal fiber laminates in terms of dynamic and static behavior. The materials that were used for fabrication of test specimen were aluminum, woven basalt fibers, an epoxy resin with a hardener, and multi-walled carbon nanotubes. The MWCNTs were used in weight percentages of 0 %, 0.1 %, 0.25 %, 0.5 % and 0.75 %. To obtain the right homogenous dispersion of the MWCNTs within the epoxy resin, and ultrasonic probe was used over a period of an hour. To enhance the interfacial bonding with the layers of fiber-epoxy and aluminum, the aluminum sheets were subjected to sulfuric acid anodizing. Addition of 0.1 wt. % and 0.25 wt.% of MWCNTs did not make any significant changes on the flexural properties. On the contrary, the addition of 0.1 wt. % resulted in a decrease within the flexural strength from almost 558 MPa to 547 MPa. However, the incorporation of 0.5 wt. % of the MWCNTs resulted in a 36.62% increase within the flexural strength and an increase in the flexural modulus of 60.16%. However, adding 0.75 wt. % of the MWCNTs resulted in a break within the sample at lower displacement as compared to composite with no CNT. The authors state that this is due to the agglomeration of MWCNTs when added in high content in addition to the creation of voids due to an increase in the viscosity of the polymer. When 0.5 wt. % of MWCNTs is added, the crack initiation and crack growth was hindered due to better interfacial bonding. Results of high velocity impact tests showed that a 0.5 wt. % of MWCNTs had the smallest damage areas. Matveeva et al. (2019) performed a numerical study to investigate the effect of two types of CNTs on a carbon fiber/epoxy unidirectional composite. The two types of CNTs induced in the composite are agglomerated CNTs in the matrix and CNTs grown on fibers. The authors conducted a transverse tensile stress test using finite element model based on an embedded element technique. The model had a fiber volume fraction of 60%. The composite with agglomerated CNTs had a lower strength and a higher transverse stiffness compared to the composite without CNTs. On the other hand, the composite with CNTs grown on the fiber showed lower stress concentrations in the matrix close to the fiber surface and higher stress concentrations around the tips of the nanotube. The high concentrations around the tips caused debonding in the matrix due to high deformations.

3. Methods

The composite prepared and tested in this study is composed of 4 layers of 450g/m2 2x2 twill carbon fiber, shown in Figure 1, impregnated in mixture of IN2 Epoxy Infusion Resin and CNTs with a fiber volume fraction of 50 %. Industrial grade multiwall carbon nanotubes with an 88+% purity, were used for the study. The outside diameter varies from 20-40 nm, an inner diameter 5-10 nm and length varying between 10-30 µm. In order to predict the effect that CNTs have on mechanical properties of the composite, different samples were prepared with different % of CNTs (0, 0.25, 0.5, 1 and 2%).

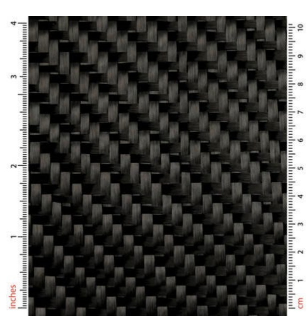

Figure 1. 450 g 2x2 twill carbon fiber

To manufacture the laminates, the resin is combined with a FAST hardener at a ratio of 100:30 to make the matrix. At the same time depending on the % wt of CNT, correct weight was measured using a scale them mixed with the matrix. The composite was then manufactured manually using wet layup process. Metallic mold was sprayed with a demolding agent then a layer of fibers was added then resin was slowly poured and brushed over the fiber layer till it is completely impregnated. The process was repeated till all 4 layers were completed then left to cure till next day before demolding for testing.

To measure the responses a tensile test was conducted using an Instron Universal testing machine (Figure 2) on a specimen size of 120 x 15 x 5 mm at a constant strain rate of 1 mm/min. Load deflection was captured during the test which was later used to plot stress-strain curves shown in figure 3. Two samples were prepared for each CNT %. The ultimate tensile strength (MPa) and toughness (J/m3) were calculated for each test.

Figure 2. Tensile test using Instron Universal testing machine

4. Results and Discussion

Figure 3 shows the stress-strain curve. Stress was calculated by diving the force applied by the original cross-sectional area of the specimen. Strain as calculated by getting ratio of change of length by original length. As seen from figure 3, the addition of CNT up until 1 % enhances the ductility of the composite without compromising the stress. The ultimate tensile stress is almost the same if not higher as the percentage of CNT increases while the strain t failure increases. Increasing the CNT % beyond 1 % reduces the ductility of the material. Its behaviour is almost similar to that without any CNT addition.

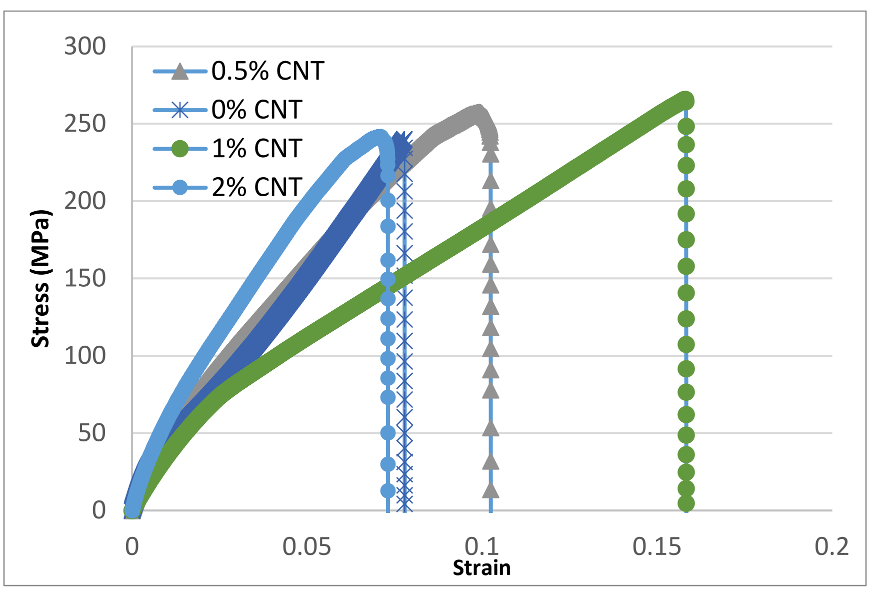

Figure 3. stress-strain curve for different CNT %

Young's modulus was calculated by computing the slope of the elastic part in the stress-strain curve while toughness was computed as the area under the stress-strain curve. Results for the toughness and elastic modulus are given in Figures 3 and 4, respectively. The results reveal that an increase in CNT % increases the elastic modulus and ultimate tensile strength of the composite up to 1 % addition. The increase in elastic modulus reaches 28 % at 1 % CNT and toughness reaches 110 %. This large increase in toughness could be attributed to the increase in strain for 1% CNT sample which reached 0.05 compared to 0.022 for 0 % CNT sample. However, the addition of CNTs in excess of 1 % yields negative effect. This could be attributed to the agglomeration of CNTs due to the Van der Waals attraction force between its crystalline ropes. The ropes tend to bind together reducing their dispersion and acting as stress concentration points weakening the material rather than improving its strength. This is clear from Figures 4 and 5 upon comparing the elastic modulus and material toughness at 2 % and 0% showing a reduction of 5% and 0.3%, respectively.

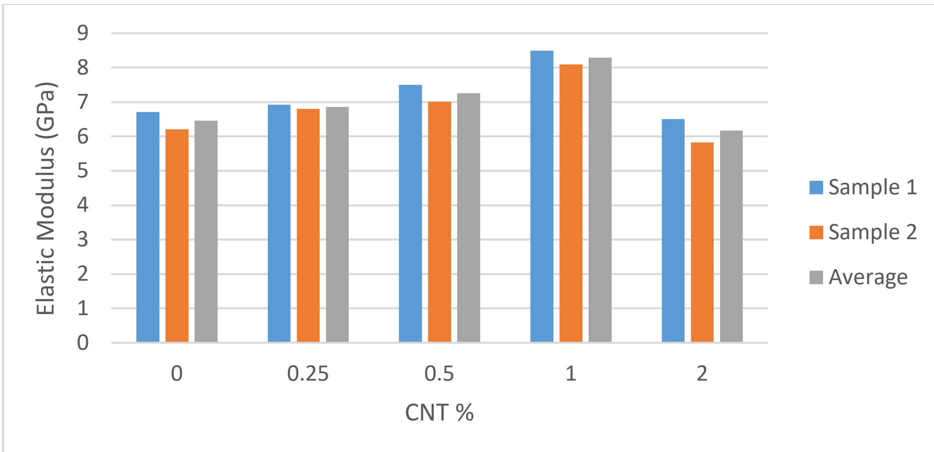

Figure 4. Elastic Modulus for different CNT %

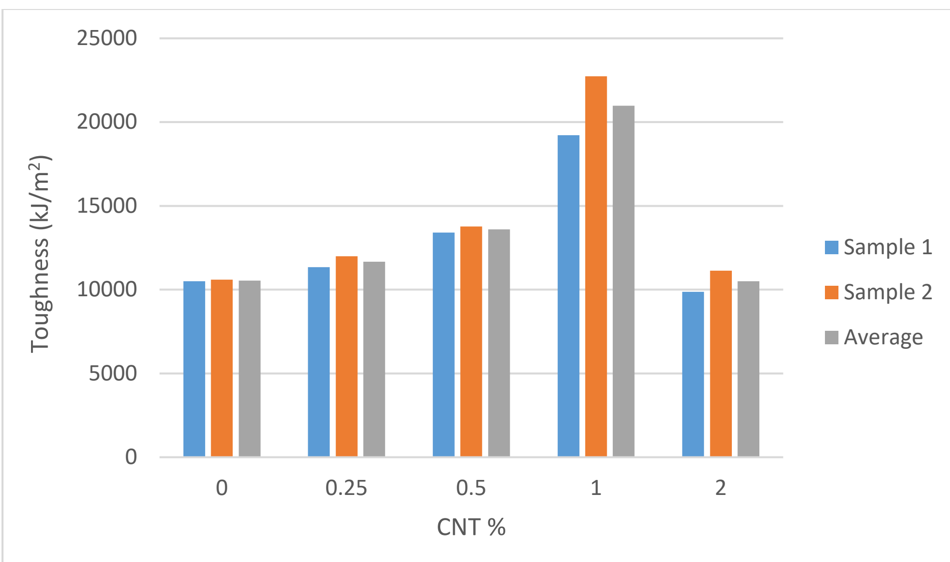

Figure 5. Toughness for different CNT %

5. Conclusion

There are mixed results in the literature regarding the effect of adding CNT toward enhancing the mechanical properties of composites. The authors attributed this to the % of CNT added. Depending on the amount of CNT added, it may lead to an enhancement in the properties or agglomeration of CNT weakening the composite structure. In this work, a wide range of CNT % was examined from 0-2%. It can be seen that the tensile behaviour of the composite is enhanced up to 1% addition but decreases thereafter. Future research work suggested by authors involves examining the combined effect of different fiber materials and fiber volume fractions and CNT %. To determine the optimum % of CNTs that enhances the strength of the composite without agglomeration.

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Biographies

Noha M. Hassan, Ph.D., is an associate professor of Industrial Engineering at the American University of Sharjah. She holds an undergraduate degree and a Master's degree in Mechanical Engineering from American University of Cairo, and a Ph.D. degree in Engineering Mechanics from Virginia Polytechnic Institute and State University, Virginia, USA. Her main research interest lies in the interrelationship between materials, manufacturing and design. Her expertise is in area of material modeling, examining material's behavior through numerical, experimental as well as microstructure analysis, manufacturing system modeling and processes optimization.

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Rami As'ad, Ph.D., received his BSc and MSc in Systems Engineering and Operations research from King Fahd University of Petroleum and Minerals, Saudi Arabia, in 2003 and 2006, respectively, and a PhD in Industrial Engineering from Concordia University, Canada, in 2010. He was a post-doc fellow at CIRRELT research center (University of Montreal) for a period of six months in 2011 where he later joined John Molson School of Business at Concordia University as an assistant professor till the end of 2013. Early 2014, he joined the Industrial Engineering Department at the American University of Sharjah as an assistant professor and got promoted to the associate professor rank in 2021. His primary research areas are supply chain management and mathematical modeling, and he has published papers in a wide spectrum of journals including International Journal of Production Economics, International Journal of Production Research, Journal of Cleaner Production, Computers and Industrial Engineering, among others. He is also a reviewer for several journals in the field.

Assil Charkaoui received her BSc in Electrical Power Engineering from Caledonian College of Engineering, Oman in 2019; and MSc in Biomedical Engineering from University of Glasgow. She is currently doing her PhD in Material Science and Engineering at the American University of Sharjah. Her primary research area during her PhD studies is in understanding material behaviour in different areas through designing, modelling, and experimenting.