IMPROVING TENSILE, FLEXURAL AND INTERLAMINAR STRENGTH OF CARBON FIBER REINFORCED POLYMER COMPOSITE LAMINATES BY COATING THE FIBERS WITH CELLULOSE NANOCRYSTALS - BONDED CARBON NANOTUBES

A Thesis

by

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ABSTRACT

The objective of this study is to make hybrid carbon fiber reinforced polymer composites with enhanced interlaminar strength using cellulose nanocrystals (CNC) and carbon nanotubes (CNT). We integrated the nanoparticles into the fibers by coating the carbon fibers through immersion and/or sonication in CNC or/and CNT aqueous suspensions prior to resin infusion through vacuum-assisted resin transfer molding (VARTM) process. Three types of hybrid CFRP samples were prepared in this work: CNC-coated, CNT-coated and CNC-CNT coated and their interlaminar strength are compared with that of composites with no nanoparticles. The incorporation of 0.2CNT-0.2CNC in the CF/epoxy composite increased the interlaminar shear strength by ~35% and flexural strength and flexural toughness by ~33% and ~46% respectively.

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Contributors

This work was supervised by thesis committee consisting of Dr. Amir Asadi as Committee Chair from Department of Engineering and Industrial Distribution, Dr. Dorrin Jarrahbashi Co- Chair, department of Mechanical Engineering.

All other work conducted for this thesis was completed by the student.

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NOMENCLATURE

CFRP	Carbon Fiber Reinforced Polymer
CNC	Cellulose Nanocrystal
CNT	Carbon Nanotube
pCNT	pristine Carbon Nanotube
SWNT	Single Walled Nanotube
MWNT	Multi Walled Nanotube
DI-H_2O	De-Ionized water
VARTM	Vacuum Assisted Resin Transfer Molding
CVD	Chemical Vapor deposition
CF	Carbon Fiber
ILSS	Interlaminar Shear Strength
SEM	Scanning Electron Microscopy

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1. INTRODUCTION

Carbon Fiber Reinforced Polymer (CFRP) composite are widely being used in the aerospace, marine, automotive industry etc. It is an extremely strong and light fiber reinforced composite with very high strength to weight ratio and stiffness. The properties of these composites can be tailored to specific property required by incorporating extra reinforcing materials, staking sequence of laminates, varying matrix material, manufacturing methods etc. The matrix material commonly used for CFRP composite is thermoset resin like epoxy, other thermoset and thermoplastic polymers like vinyl ester, polyester etc. are also being used.

CFRP composites are manufactured by various process among which out- of -autoclave process and vacuum assisted resin transfer molding (VARTM) are the most common methods used [1-5]. The main disadvantage or drawback of CFRP composite is delamination failure where the material fractures into layers and low interlaminar shear strength. The laminate structure of CFRP composite made them subject to fail through delamination as the load being capabilities of these composites is highly compromised. These failures are very catastrophic as the failure develops inside of the material without being obvious on to the surface [6]. Methods such as z spinning [7], stitching [8] and 3D weaving [9] have been introduced to improve the interlaminar shear strength (ILSS). Another technique to prevent this delamination failure and to improve the interlaminar properties is to enhance the adhesion between the laminates or layers of these composites. Many researches show that introducing nanoscale particles to the matrix or fiber sizing can improve the mechanical properties of CFRP composites, especially matrix dominated properties like flexural and interlaminar shear [10]. The incorporation of nanomaterial not only improve the adhesion between the laminates but also increase the toughness of the material by resisting crack propagation [11].One reliable method to achieve this is by introducing carbon nanotubes (CNT's) as fillers in the fiber reinforced composites because of their excellent intrinsic properties and unique shape. They are a good candidate for stitching the layers of carbon fiber together and increase the interlaminar adhesion. Also, there is a need for improvement in thermal and electrical conductivity of CFRP composites and incorporating CNT helps in improving these properties [12,13]. So, these nanoscale reinforcements may overcome the typically microscale defects seen in such type of composites and make CNT's an ideal filler material.

Recently a significant number of researches have been conducted for incorporating CNT's as reinforcement in CFRP composite. The main methods used for this purpose are i) Chemical vapor deposition (CVD), where CNT's are grown on carbon fiber surfaces [14,15], ii) dispersion of CNT directly into resin [16,17] by sonication and stirring iii) interlayering, where resin rich layers is introduced between adjacent CF piles and iv) spraying or immersing CF in CNT suspension [19,20] v) electrophoresis where particles suspended in liquid medium migrate in an electric field and get deposited on to the fiber surface. All these methods have drawbacks like increasing viscosity of resin as CNT concertation increases leading to incomplete matrix infusion, damaging primary carbon fiber during CNT growth and difficulty in controlling the uniformity of CNT deposition during CVD process and uneven deposition of CNT on fiber surface in electrophoresis and spraying methods [21]. Moreover, these techniques are not scalable and cannot be used in industrial scale production.

In this paper we introduce a scalable technique to incorporate CNT in CFRP composite using cellulose nanocrystals (CNC). We show that CNC will improve the dispersion and stabilization of hydrophobic pristine CNT in water and thus prevents agglomeration. Figure 1.1 summarizes the stages and the outcome of this project. The initial focus is on the processing i.e. dispersion and stabilization of CNT in an aqueous suspension by the addition of CNC. Once the involving parameters have been defined, CNC-CNT will be integrated in hybrid CFRP composites by immersing the CF in CNC-CNT aqueous suspension to create Nano stitches between the laminates or layers of the composite. Then, the coated CF layers are used in manufacturing of hybrid composites using vacuum assisted resin transfer molding (VARTM). The microstructure, properties, intralaminar shear etc. of the hybrid composites are evaluated.

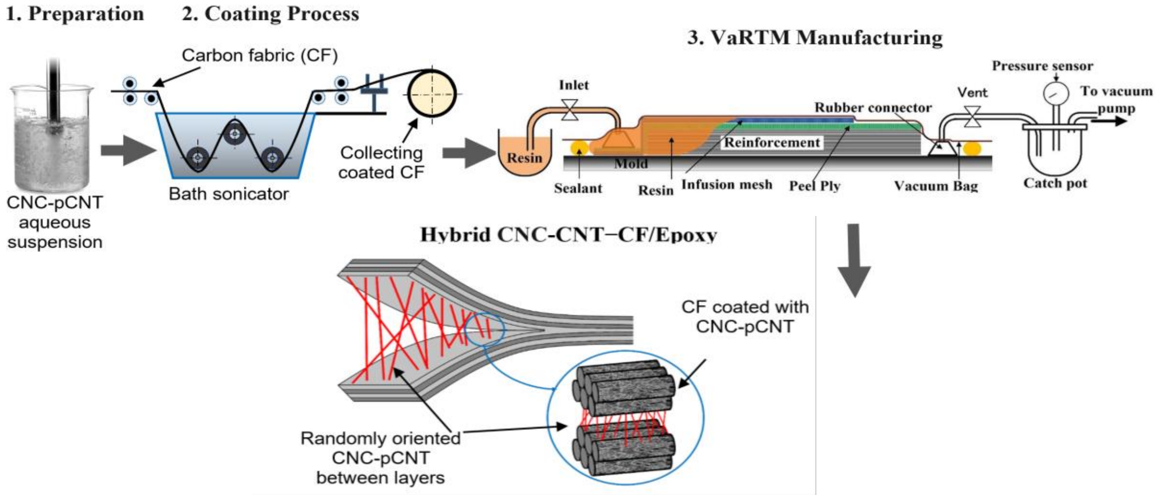


Figure 1.1 Overview of methods- Process- Manufacturing of hybrid composite

1.1. Cellulose Nano Crystals

Cellulose is the most abundant polymer on earth and is a ribbon like glucose molecule. It is the building block of plants and hence plants and trees are the main source of cellulose. The two different type of nanocellulose is Cellulose Nanocrystals (CNC)and Cellulose Nanofibrils (CNF). CNC is obtained from native fibers through acid hydrolysis and CNF is obtained through homogenization, microfluiodization and grinding methods. CNC has widespread applications in the fields of biomedical, water treatment, energy and electronics because of its remarkable strength, biodegradability and renewability [22,23]. The density of CNC is 1.6g/cm^{3}and the tensile strength ranges from 2-7.5 GPa. So has the properties of some of the best fibers like Kevlar and Carbon. Due to these advantages, they can be applied into various industries such as packaging, filtration, artificial skin, and cosmetics [24].

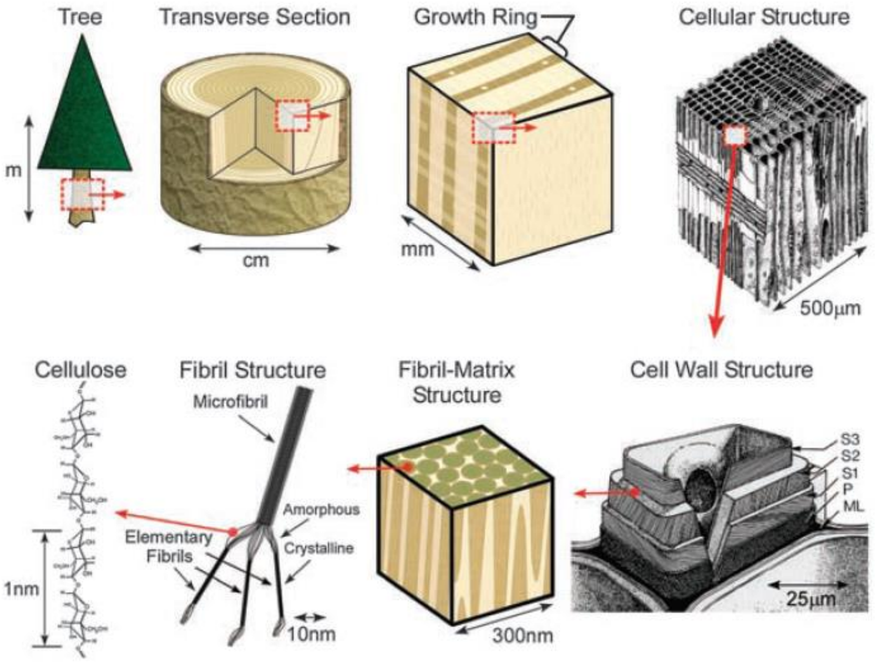
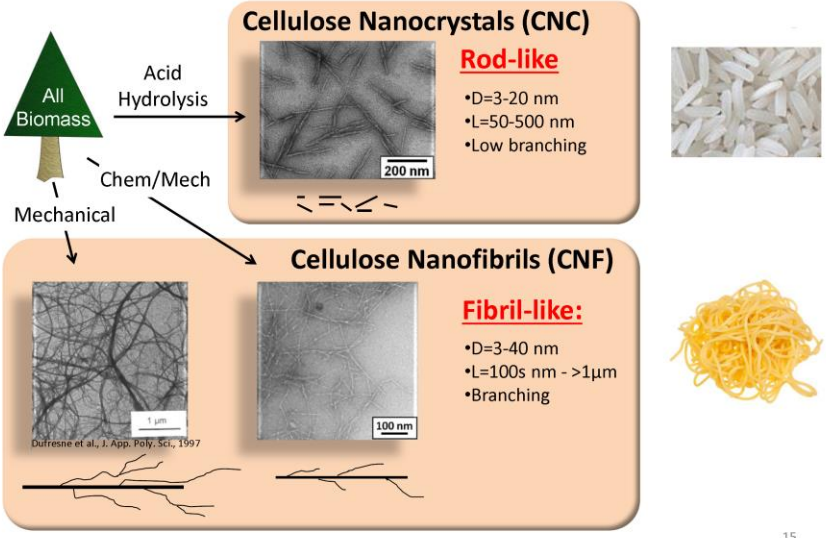


Figure 1.2 Schematic of tree hierarchical structure Reprinted from [24]

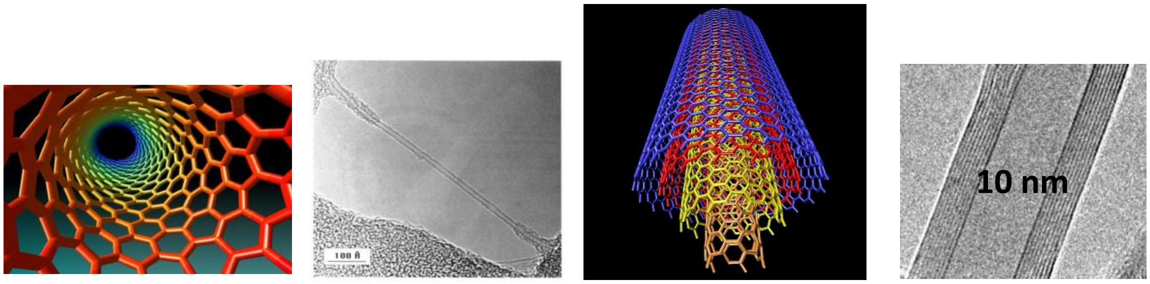


Dufresne et al., J. App. Poly. Sci., 1997

Figure 1.3 Different types of Cellulose nanomaterials

1.2. Carbon Nanotube

Carbon nanotube (CNT) is an allotrope of carbon which is a class of nanomaterial that consist of a two-dimensional hexagonal lattice of carbon atoms, joined to form a hollow cylinder. They have diameter in the range of nanometer and is mainly classified into Single Walled Nanotube (SWNT) and Multi Walled Nanotube (MWNT). SWNT is one atom thick layer of graphene rolled into a seamless cylinder where as MWCT consists of multiple rolled concentric layers of graphene. CNT is one of the strongest, flexible and stiffest material discovered and have very good thermal and electrical conductivity along the tube. They have very high tensile strength and elastic modulus as well and hence they are used in wide variety of application like in nanotechnology, electronics, optics and in the field of material science.



SWNT (Single Wall Nanotube) **MWNT (Multi-wall Nanotube)**

Figure 1.4 Categories of carbon nanotubes
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2. EXPERIMENTAL METHODS

2.1. Materials

The carbon fiber used in this work is plain woven with 3K tow size and the resin is bicomponent epoxy resin consisting diglycidyl ether of Bisphenol-A epoxy 635 thin epoxy and 556 slow polyamide hardeners supplied by US Composites (Wes Palm Beach, FL). Cellulose Nano Crystals (CNC), is provided by CelluForce (diameter of 2.3-4.5 nm and length of 44-108 nm) with a tensile strength of 5GPa and elastic modulus of 150GPa. Carbon nanotube (CNT) is purchased from Nanocyl, Belgium and we are using NC 7000 MWNT (average diameter of 9 nm and length of 1.5 µm).

2.2. Preparation of aqueous suspension

Aqueous suspension of CNC is very easy to prepare and was prepared by tip sonicating different weights of CNC (for different concentration of suspension) in 250 ml of deionized water (DI-H_2O) for 20 minutes at a frequency of 20kHz and an amplitude of 75% in a Qsonica Q125 sonicator equipped with a sonotrode of a 6 mm diameter. For the dispersion of CNT in water without CNC functionalization must be done, which is a very harsh process and will also cause a lot of damage to the walls of the CNT which will impair its properties. Functionalization is the modification of CNT surface to reduce its hydrophobicity and prevent agglomeration. The CNT suspension was prepared by oxidizing raw CNT in 3:1 mixture of H2SO4:HNO3 by bath sonication at different temperature and time period. 250 mg of raw CNT was added to a 3:1 vol ratio of concentrated Sulphur and nitric acid and ultrasonicated in a sonication bath for 2 h at 23 ˚C [25]. The suspension was then stirred in an oil bath for 5 h at 60 ˚C in case of harsh treated CNT and for 2h in case of mild treated CNT. After oxidation, the CNT was isolated with a polyvinylidene fluoride (PVDF) filter membrane under vacuum and washed four times with DI-H2O during the filtration process to remove any trace of acid residue. The suspension of different concentration of pristine CNT (pCNT) and CNC in DI-H2O was also prepared by tip sonicating 1:1 ratio of pCNT and CNC (different weights for different concentration) for 2hrs in 250ml of with DI-H2O at an amplitude of 75%. An ice bath was used so that the temperature of the suspension will not increase while sonicating. Figure 2.1 shows the dispersion of various nanomaterials in DI-H2O. From the figure we can see that CNC stabilize and disperse pCNT in water.

CNC and/or pCNT in
aqueous suspension

Figure 2.1 Tip sonication of aqueous suspensions

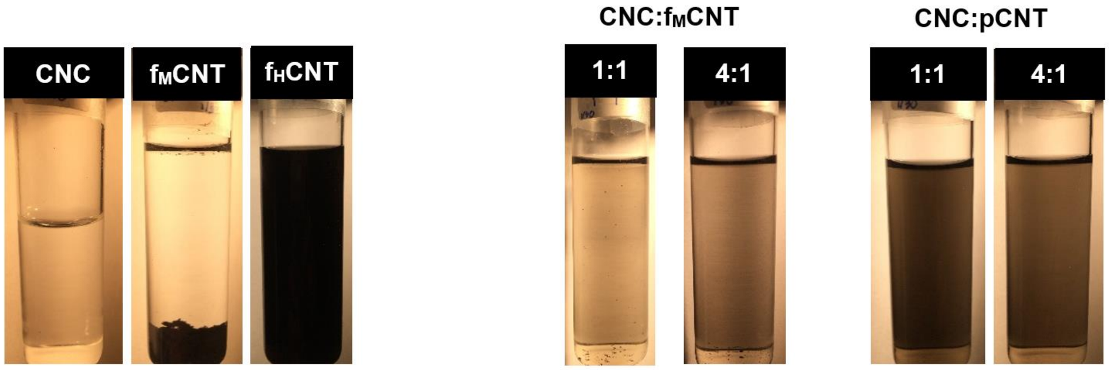

Figure 2.2 Stability and dispersion of CNC and/or CNT in water

2.2.1. Mechanism

The addition of hydrophilic CNC improves the stability and dispersion of hydrophobic CNT in aqueous suspension and thus prevents agglomeration. The mechanism behind this is that when mild treated CNT and CNC suspension is prepared the hydroxyl (-OH) groups on the CNC forms stronger hydrogen bonding with the carboxyl (-COOH) groups of mildly oxidized CNT. In the case of CNC and pCNT new covalent bonds are formed between the -OH groups of CNC and defects in pCNT. This inhibits the weaker Van-der Waals forces between neighboring CNT and hence prevent agglomeration.

2.3. Coating of fibers with Nanomaterial for Nano stitching

The integration of CNC and /or CNT on to the CF layers was done by two different methods. (i) Dipping / immersion – here the fibers were dipped in bath filled with the aqueous suspension of CNC and /CNT and was immersed in it for 20 min. It was then dried in room temperature for 12h. (ii) Sonication while dipping – In this case the CF layers was dipped in a bath sonicator filled with CNC and/or CNT suspension. It was then sonicated for 5min and then dried at room temperature for 12h. These coated fibers are then baked in oven at 180° F for 30 min before being manufactured into composite.

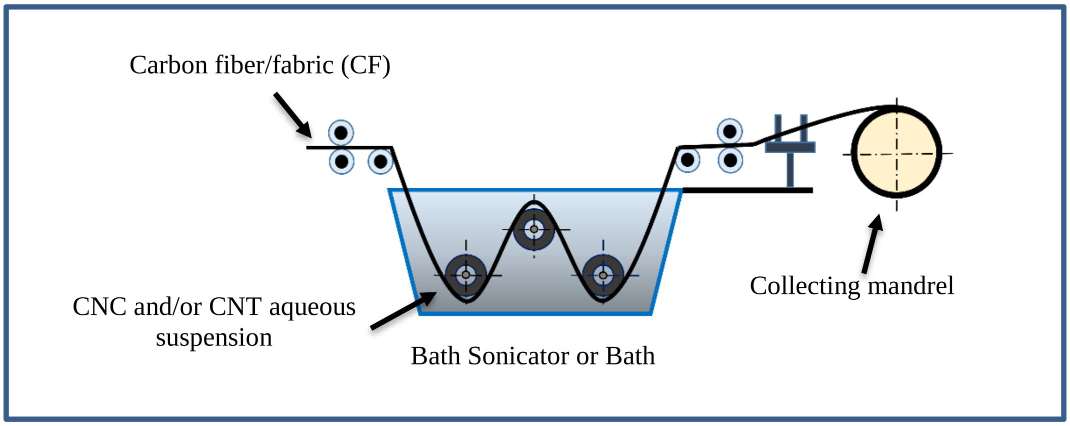

Figure 2.3 Coating of nanomaterial on CF layers

2.4. Manufacturing of Hybrid Composite

The samples were manufactured by Vacuum Assisted Resin Transfer Molding (VARTM) process, which is a three-step process (i) Reinforcement preform lay-up (ii) Perform impregnation with resin by vacuum (iii) Resin curing. They were prepared using eight plies CF and 70 wt. % epoxy. As schematically shown in figure 2.4 the fibers coated with CNC and /or CNT were placed on a mylar (polyester) film. Then a layer of peel ply was added over the carbon fibers to prevent sticking of the final fabric on to the mold and a part of it was on the mold near resin inlet and outlet connectors to direct and increase the resin flow. Infusion mesh was put on the peel ply over the carbon-fiber area to enhance the resin flow. The entire package was enclosed in a vacuum bag and sealed with two-sided butyl tape. Two external hoses were connected to the inlet of the resin source and the vent to the vacuum pump. Prior to resin infusion, the inlet was closed, and the vacuum pump was turned on to draw the air trapped inside the mold. After establishing the vacuum, degassed resin was infused from the inlet. The excess resin was removed from the vent, led to the catch pot (shown in Figure 2.4). Then, the inlet was closed, and the vent was left open until the resin was cured. When the resin was cured completely (about 24 h later), the CFRP laminate was removed from the mold. The samples were cut from each plate using waterjet for various mechanical characterization tests. Five concentration of CNC coated composites namely 0.2 CNC, 0.5 CNC, 1 CNC 1.5 CNC and 1 CNC-S was manufactured. For functionalized CNT seven concentration samples were prepared, namely 0.01 CNT, 0.05 CNT, 0.2 CNT,0.4 CNT, 0.5 CNT, 0.2 CNT-S and 0.5 CNT S. For CNC- pCNT, 0.2 CNC-0.2 CNT, 0.5 CNC-CNT and 0.2 CNC-0.2 CNT-S was fabricated. Along with these samples neat CFRP composite was also fabricated for comparison purposes.

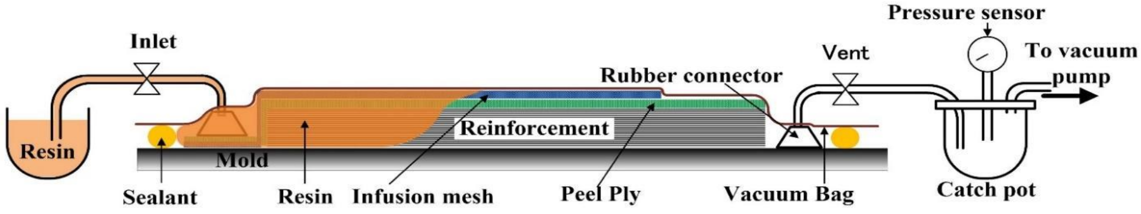

Figure 2.4 Schematic setup of VARTM

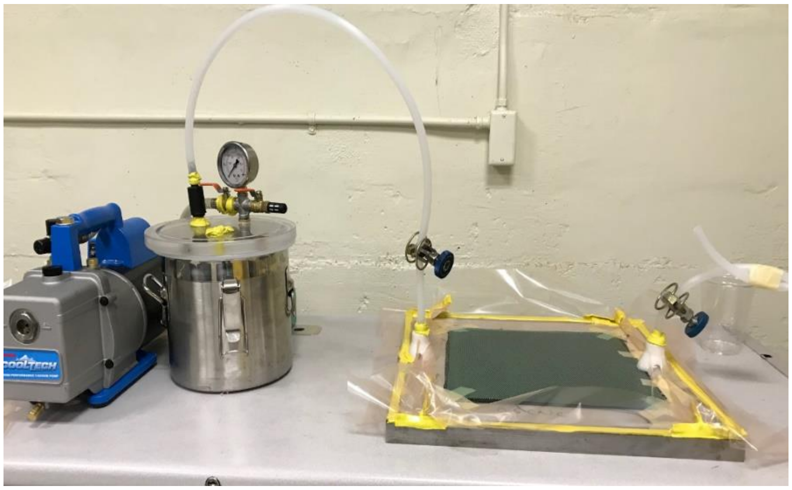

Figure 2.5 VARTM setup

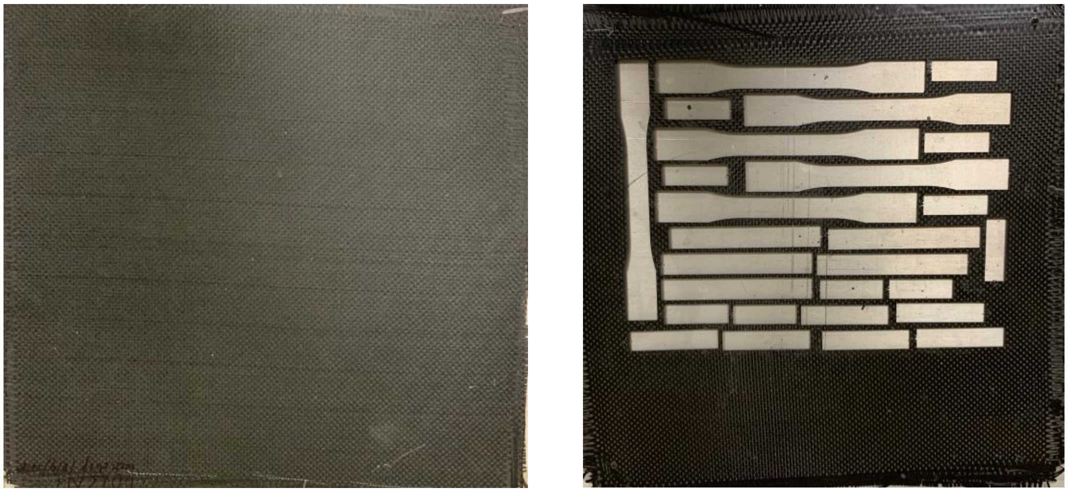

Figure 2.6 Manufactured plates before and after waterjet cutting

3. CHARACTERIZATION TECHNIQUES

3.1. Scanning Electron Microscopy

After the coating of nanomaterial was done on the CF layers SEM micrographs of the fibers was taken to analyze the coating, its uniformity and distribution. A JCM - 5000 Neoscope tabletop scanning electron microscope (SEM) at an acceleration of 15 kV was used to study the coating of CNT and/or CNC on the surface of the carbon fiber sheets.

3.2. Thermomechanical characterization

3.2.1. Short Beam Test

To determine the interlaminar shear strength (ILSS) of CFRP composite short beam test was carried out. The test was conducted according to ASTM D2344 standard and the specimen were tested on a United Universal testing Machine (UTM) with a 2kN load cell. The specimen dimensions were 40mm in length 12mm in width and 2.1mm in thickness with a span length of 25.4mm. Each ILSS value is an average of at least 10

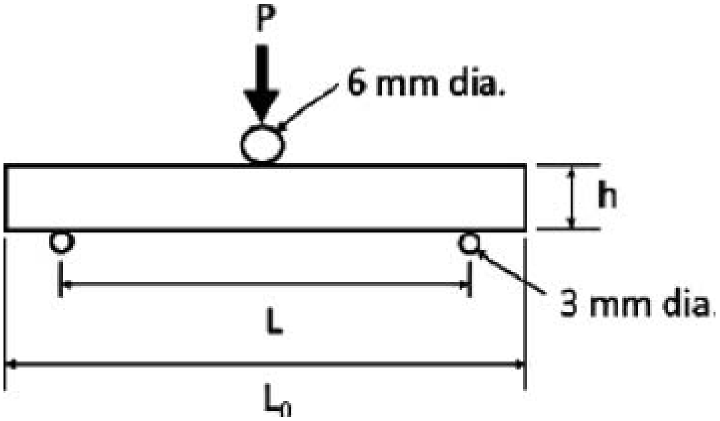

Figure 3.1 Schematic of short beam test setup reprinted from [26]

samples. As shown in figure the specimen was placed on the cylindrical supports and load was applied by the movement of a cylinder head at the center of the specimen until the first failure is documented. The test was stopped after the specimen failed in one of the following three modes (i) Interlaminar shear (ii) Flexural tension/ compression (iii) Inelastic deformation. The load at failure is then used to calculate the interlaminar shear strength. The interlaminar shear strength was calculated according to the formula

$$Strength = 0.75 \times \frac{Maximum\ load}{width\ \times thickness}$$

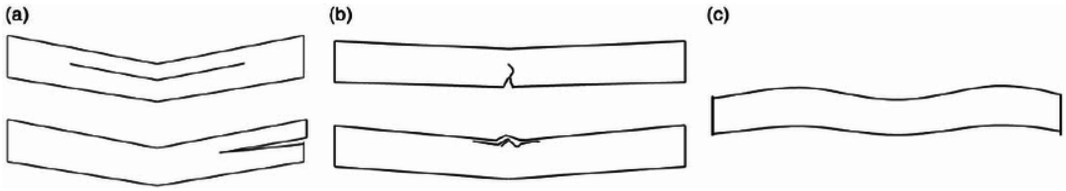

Figure 3.2 Failure Modes in Short beam test reprinted from [27]

3.2.2. Flexural and Tensile Test

Flexural test was conducted according to ASTM D790 standard with a 2kN loadcell on United UTM to determine the Flexural strength, modulus and toughness of CFRP composite. The specimen dimensions were 96mm X 13mm X 2.1mm with a span of 86mm. The specimen was loaded until a peak load is reached and then the load drops to about 60% of peak load and the material fails.

According to ASTM D638 standard tensile properties of the samples were determined on a United UTM with a 10kN load cell. The samples were dog bon shape with length of 165mm and gauge length of 50.8mm. Each tensile and flexural data is an average of at least seven samples.

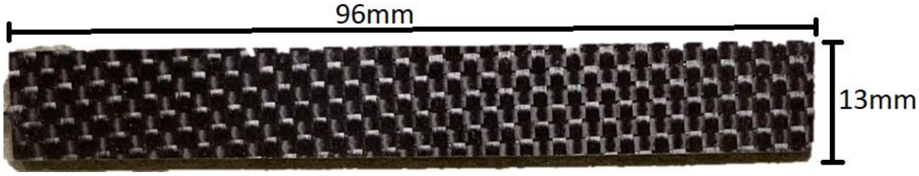

Figure 3.3 Flexural test specimen

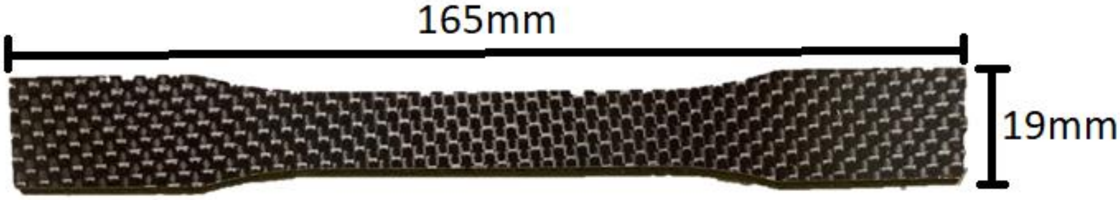

Figure 3.4 Tensile test specimen

3.2.3. Dynamic Mechanical Analysis

The dynamic mechanical analysis in dual cantilever mode was used to determine the tan delta and storage modulus and to validate the work. The samples were tested on DMA Q800 from TA instruments. The temperature ramp for the test was 3°C/min from a temperature of 30°C to 100°C at a frequency of 1Hz. The test was conducted according to ASTM D 7028 with specimen dimensions of 60mm x 13mm x 2.1mm.

4. RESULTS AND DISCUSSION

In this research project, in order to test the hypothesis that the addition of CNC bonded CNT can improve the mechanical properties, the test results were obtained, and a comparison was drawn between the composite coated with both the technique and neat CFRP composite. The testing of the samples was aimed to evaluate its strength and its ability to take impact. In order to evaluate the mechanical properties, the three-point bending test or flexural test, inter-shear laminar test or short beam test and tensile test were conducted. The flexural test and tensile test performed on the composites provided a quantitative insight of the strength and toughness of these composite.

4.1. Scanning Electron Microscopy

After the coating was done on the CF layers by two different techniques SEM micrographs of the fibers were taken to evaluate the coatings. Figure 4.1 shows the coating of the nanomaterials on the fiber surface with sonication while dipping and dipping coating process. There is a difference in the dispersion and distribution of Nano particle in the two-technique used. For CNT- CNC and CNC the coating has increased tremendously but there is agglomeration when sonicated during the coating process. CNT doesn’t show any significant improvement in the coating of the nanomaterials with sonication, but agglomeration is less in case of sonication while dipping.

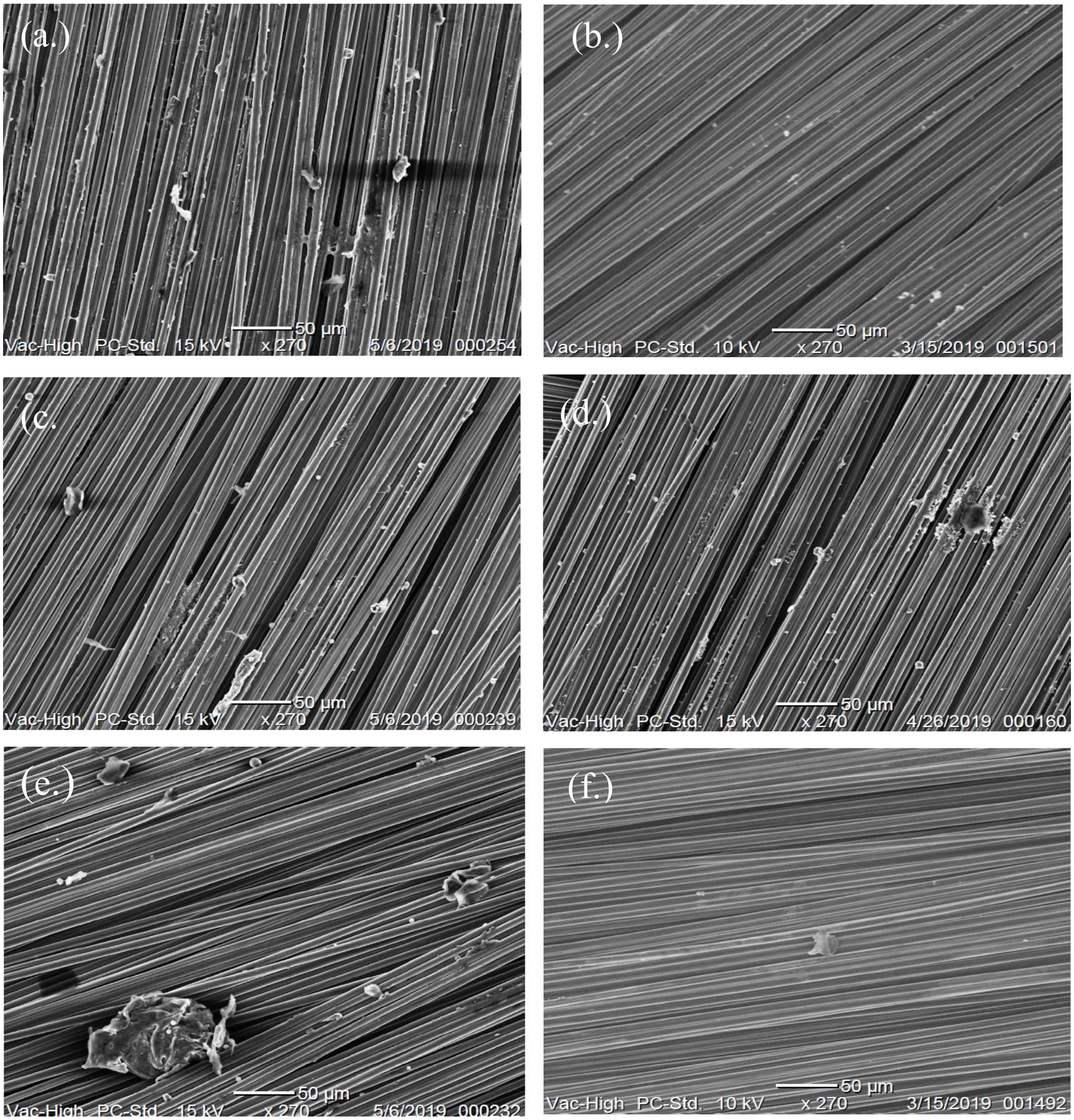

Figure 4.1 SEM micrographs of 0.2 CNT-0.2 CNC a.) Sonication while coating, b.) No sonication, 0.2 CNT c.) Sonication while coating, d.) No sonication and 1wt CNC e.) Sonication, f.) No sonication

4.2. Interlaminar Shear Strength

Short beam test is the most popular test used to determine the ILSS properties of fiber reinforced composites through bending. The estimation of ILSS using short beam testing is centered on the classical beam theory. During short beam test the failure mechanism are a combination of compression, tensile and shear deformations. The ILSS value of different composites are shown Figure 4.2. From the figure we can see that the composite with the highest ILSS value is 0.2 CNC-0.2 CNT followed by 0.2 CNC and 0.5 CNC- 0.5 CNT. There is a 35% increase in the ILSS value when compared to the neat CFRP composite and 29% increase when compared to the 0.2 CNT functionalized sample. The maximum ILSS value reported is 29.2 MPa whereas for neat CFRP the value is 21.6 MPa

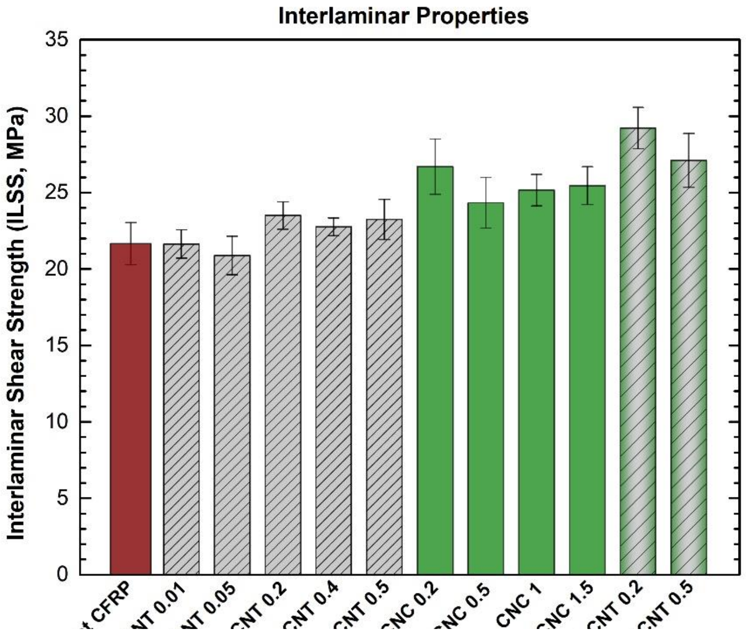

Figure 4.2 Effect of CNT and/or CNC content on the interlaminar shear strength of CFRP composite

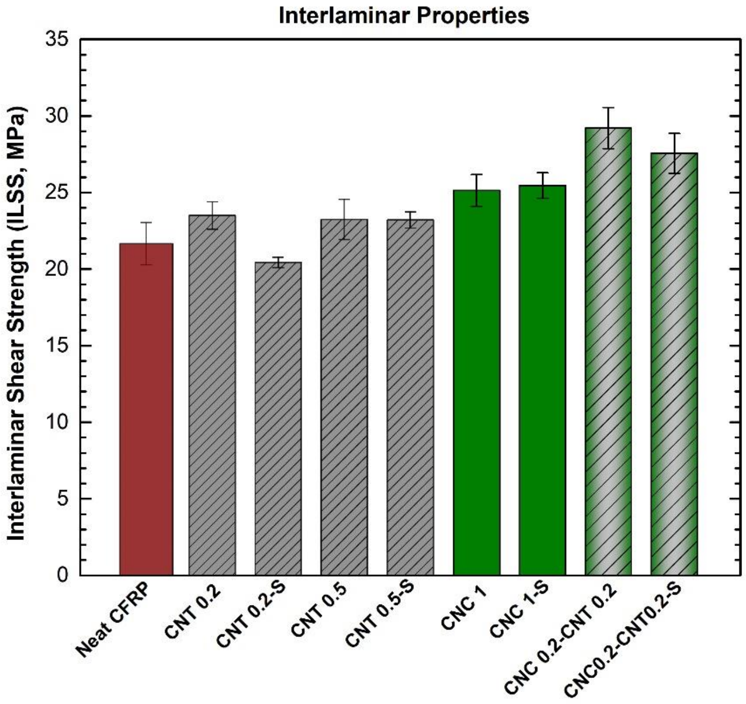

Figure 4.3 Effect of CNT and/or CNC coated with and without sonication on the interlaminar shear strength of CFRP composite

Figure 4.3 shows the comparison of ILSS value of composite coated by the two different methods i.e. dipping and sonication while dipping. The samples coated using sonication while dipping had higher ILSS value when compared to the neat CFRP sample but did not show any improvement in the property when compared to the samples coated with only dipping. This is can be attributed to that fact that there is some agglomeration in the sonicated samples as shown in the SEM images earlier.

4.3. Flexural Test Results

Figure 4.4 elucidate the flexural strength, moduli, toughness and strain at break of the various CFRP composites. The 0.2 CNC- 0.2 CNT composite showed the highest strength and modulus of flexural. There is a 33% increase in the flexural strength and 14% increase in the moduli when compared to the neat sample and 40 % increase in strength when compared to the functionalized CNT of same concentration. Highest flexural toughness is reported by 0.5 CNC-0.5 CNT with an increase of 46% when evaluated with neat CFRP. The maximum flexural strength reported was 554MPa for 0.2 CNC-0.2 CNT composite. Amongst the CNC samples 1 CNC showed the highest strength and moduli with an increase of 13% in strength and 1.5 CNC showed the highest toughness. Among the functionalized CNT samples 0.4 CNT showed the highest strength with an increase of only 6% when compared to neat CFRP.

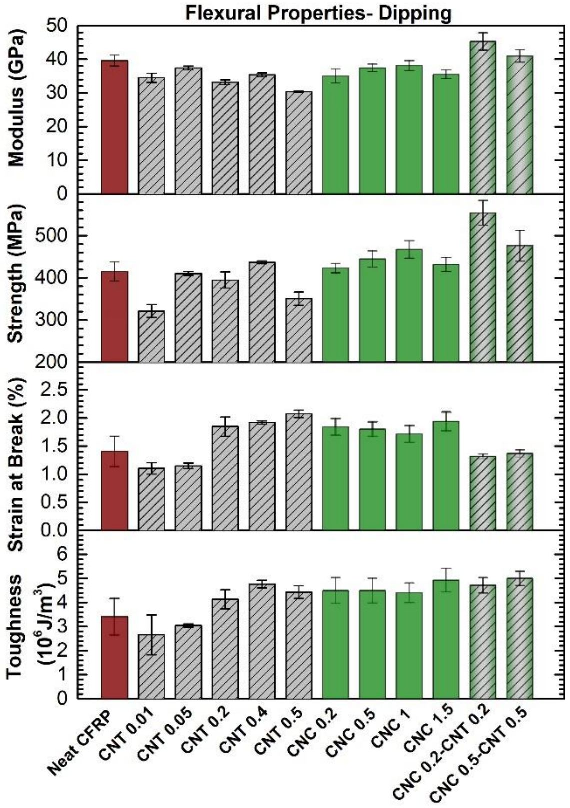

Figure 4.4 Effect of CNC and/or CNT content on the Flexural properties of CFRP composite

Figure 4.5 shows the comparison of the samples that were coated using sonication while dipping and without sonication. There is no significant increase in the flexural properties when coated while sonicating compared to the dip coating. Only 0.2 CNT- S have some improvement in the strength and modulus when compared to the sample coated without sonication. This can be attributed to the coating of Nano material on the fibers from the SEM images there is agglomeration in the samples coated with dipping when compared to the samples coated with sonication while dipping. Hence it shows that incase of functionalized CNT samples sonication while dipping.

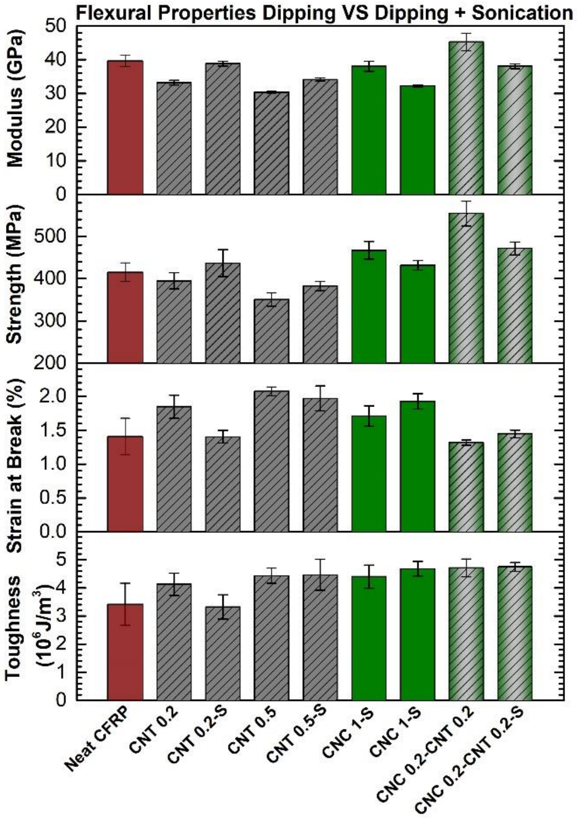

Figure 4.5 Effect of CNT and/or CNC coated with and without sonication on the Flexural properties of CFRP composite

4.4. Tensile Test Results

The effect of CNT and /or CNC content on the CFRP composites is plotted in figure 4.6. The incorporation of 0.5 CNC-0.5 CNT increased the toughness of the composite by 14% but there is not significant effect of it on the moduli and strength of the composites. The CFRP composites are already good in tensile properties and there is no delamination here, hence the incorporation of nanomaterial couldn't increase these properties any further. Also, the tensile properties did not compromise when coated with CNC bonded CNT.

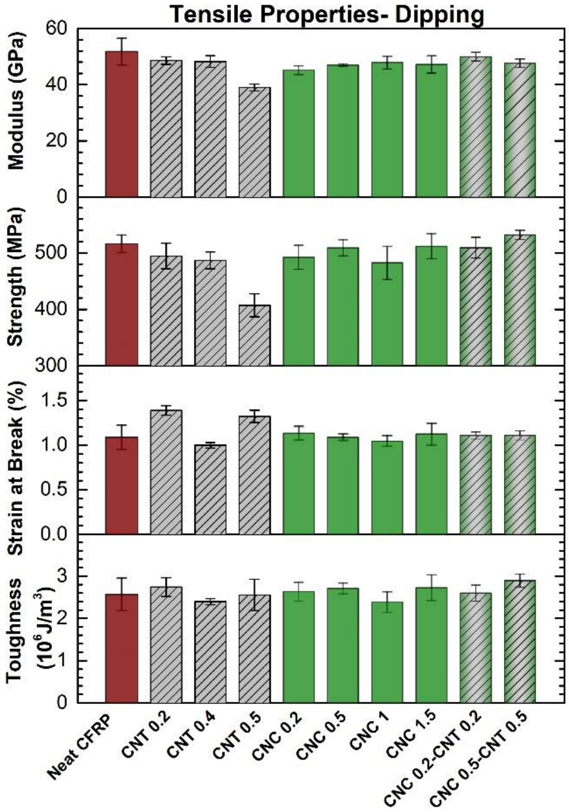

Figure 4.6 Effect of CNC and/or CNT content on the Tensile properties of CFRP composite

Figure 4.7 shows the comparison between the samples that was coated using sonication and the ones without sonication. Similar to the flexural results, there is no significant increase in the properties except 0.2 CNT-S and 1 CNC -S with an increase in strength and toughness.

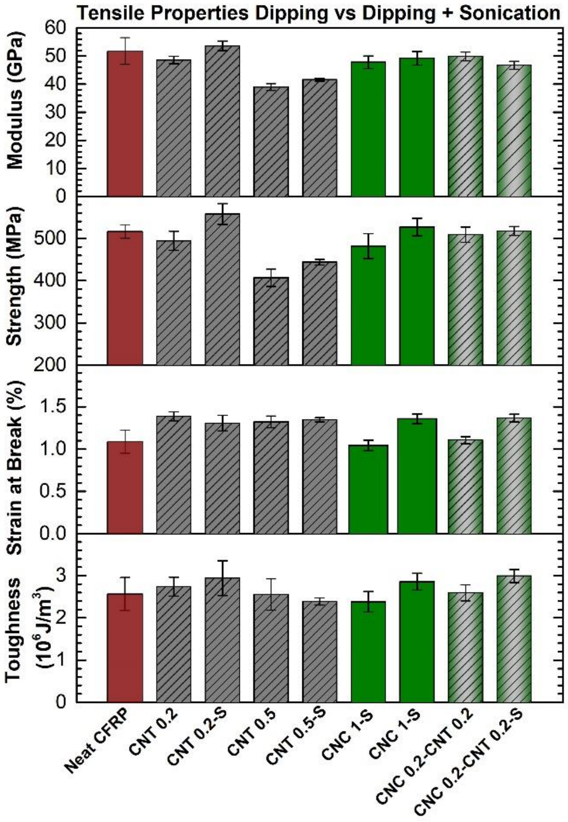

Figure 4.7 Effect of CNT and/or CNC coated with and without sonication on the Tensile properties of CFRP composite

4.5. Dynamic Mechanical Analysis

The dynamic mechanical properties of the different composites are given in Table 4.1. From the results we can see that adding nano material i.e. CNC and / or CNT did not change the glass transition temperature of CFRP composite which shows that it did not impair any of its properties. Also, there is an increase in tan delta values which shows that the toughness of the CFRP composite increase when nanoparticles are incorporated in them.

Table 4.1 Dynamic Mechanical Analysis properties

Composite	**T_g [°C]**	**tan δ at T_g**	**tan δ at Peak**
Neat	50.91 ± 0.453	0.34 ± 0.010	0.630 ±0.003
0.2 CNC	49.63 ± 1.08	0.386 ±0.014	0.658 ±0.007
0.5 CNC	49.59 ± 0.70	0.352 ±0.010	0.610 ±0.043
1 CNC	50.18 ± 0.303	0.398±0.023	0.609 ±0.027
1.5 CNC	50.21 ± 0.827	0.382 ±0.039	0.615 ±0.023
0.2 CNT	50.30 ± 0.500	0.409 ±0.044	0.638 ±0.042
0.5 CNT	51.30 ±0.721	0.375 ±0.040	0.646 ±0.003
0.2 CNT-0.2 CNC	50.9 ± 0.491	0.372 ±0.029	0.6141 ±0.024
0.5 CNT- 0.5 CNC	50.6 ± 0.848	0.369±0.001	0.6379±0.036
0.2 CNT-0.2 CNC – S	50.31 ± 0.954	0.364 ±0.032	0.664 ±0.015
0.2 CNT – S	50.99 ± 0.625	0.328 ±0.002	0.432 ±0.007
0.5 CNT – S	51.15 ± 0.325	0.360 ± 0.025	0.632 ±0.015
1 CNC - S	50.92 ± 0.339	0.361 ±0.003	0.637 ±0.011

5. SCOPE FOR FUTURE WORK

(i) Effect of humidity on the mechanical properties and interlaminar properties as CFRP composites are mainly used in marine and aerospace industry where they will be exposed to moisture. This can be done by conditioning the samples in humidity chamber and then test for the various properties

(ii) The underlying mechanism for the increase in the properties after the incorporation of nanomaterial. This can be determined by looking into the interfacial properties, which is the heart of composites. If we have a very good interface between the fiber and matrix, there is an increase the properties.

6. CONCLUSIONS

This study verified that incorporating a small amount of CNC bonded CNT in the form of a coating on CF layers can enhance the interlaminar shear properties and mechanical properties of CFRP composites without increasing the weight. Initially the aqueous suspension of nanomaterial required for coating was prepared. For this we came up with CNC assisted novel scalable technique to stabilize, disperses and integrate pristine CNT on the CF layers. The CNT was integrated on CF layers by two simple methods (i) Dipping (ii) Sonication while dipping. These CF layers were then manufactured into CFRP composite plates using VARTM process. Final stage was the to conduct various mechanical and interlaminar test to characterize the properties of the composite. From these tests it has been shown that

(i) Flexural strength of 0.2 CNC - 0.2 CNT increased by 33% compared to neat CFRP composite and 40 % compared to functionalized 0.2 CNT and the maximum flexural strength reported was 554MPa.

(ii) ILSS of 0.2 CNT- 0.2CNC increased by 35% and 29% compared to neat CFRP and 0.2 CNT.

(iii) Highest flexural toughness was reported by 0.5 CNC-0.5 CNT with an increase of 46% when evaluated with neat CFRP

(iv) The incorporation of 0.5 CNC-0.5 CNT increased the tensile toughness of the composite by 14%.

Hence, by just simply coating the fibers with nanoparticles can increase the properties of CFRP composites

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