

EXPERIMENTAL EVALUATION ON THE LONGITUDINAL COMPRESSIVE STRENGTH OF CARBON NANOFIBERS Z-THREADED CFRP LAMINATE MANUFACTURED BY THE MAGNETIC COMPACTION FORCE ASSISTED ADDITIVE MANUFACTURING METHOD

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ABSTRACT

The matrix sensitive weaknesses of Carbon Fiber Reinforced Polymer (CFRP) laminates are usually magnified by mainstream additive manufacturing (AM) methods due to the AM-process-induced voids and defects. In this paper, a novel Magnetic Compaction Force Assisted-Additive Manufacturing (MCFA-AM) method is used to print Carbon Nanofibers (CNF) Z-threaded CFRP (i.e., ZT-CFRP) composite laminates. The MCFA-AM method utilizes a magnetic force to simultaneously support, deposit, and compact Continuous Carbon Fiber Reinforced Polymer (C-CFRP) composites in free space and quickly solidifies the CFRP part without any mold; it effectively reduces the voids. Past research proved that the zig-zag threading pattern of the CNF z-threads reinforces the interlaminar and intralaminar regions in the ZT-CFRP laminates manufactured by the traditional Out of Autoclave-Vacuum Bag Only (OOA-VBO) method, and enhances the matrix sensitive mechanical, thermal, and electrical properties. In this study, the longitudinal compressive test (ASTM D695, i.e., SACMA SRM 1R-94) was performed on the MCFA-AM printed ZT-CFRP laminate. The results were compared with unaligned CNF-modified CFRP (UA-CFRP), control CFRP, and no-pressure CFRP samples' data to investigate the impact of the CNF z-threads and MCFA-AM process on the CFRP's performance. The 0.5-bar MCFA-AM printed ZT-CFRP showed comparable longitudinal compressive strength with the 1-bar OOA-VBO cured CFRP.

Keywords: Magnetic Compaction Force Assisted-Additive Manufacturing, Carbon Nanofiber Z-threaded CFRP, longitudinal compressive strength

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1. INTRODUCTION

Composite parts made of carbon fibers are used in various applications owing to their lightweight and high strength to weight ratio. The main problems lie in the unwanted formation of air gaps, physical interlayer voids, and less than compatible ratio between carbon fiber and resin content. Furthermore, CFRP laminates manufactured through traditional methods are more vulnerable to

matrix-sensitive damages, e.g., shear failure, longitudinal compressive failure, and delamination. Carbon fiber buckling significantly compromises the longitudinal compressive strength of a CFRP laminate since the relatively much softer matrix provides little support in the transverse direction to stabilize the carbon fibers [1]. Earlier studies by Hsiao et al. [2] had shown that low concentration of CNF z-threads would be capable of improving the mechanical, thermal, and electrical properties. The study showed that additional reinforcement from the CNF z-threads could improve Mode-I interlaminar fracture toughness mean value of a plain weave CFRP laminate by ~29% when using 0.3 wt% CNF z-threads, whereas all the laminates were cured using the Out of Autoclave-Vacuum Bag Only (OOA-VBO) method. In a different study, Hsiao and Ranabhat [3] showed a radial flow alignment (RFA) process to stitch CNF z-threads [4] into the unidirectional carbon fiber fabric increased the through-thickness DC electrical conductivity up to 100 times that of CFRP laminates without z-threaded CNFs. Furthermore, Scruggs et al. conducted research on the through-thickness DC electrical conductivity of ZT-CFRP unidirectional laminates and discovered the conductivity increased by 1508% and 238% with 0.1 wt% CNF for T700 fiber [5] and 1.0 wt% AS4 fiber [6] respectively while compared to control (unmodified) CFRP samples.

Kirmse et al. [1] reported that in terms of the longitudinal compressive strength, the ZT-CFRP laminates had an improvement of approximately 25% (from 619.84 MPa to 773.76 MPa) when compared to unaligned CNF-modified CFRP (UA-CFRP) laminates cured via the OOA-VB method; and the ZT-CFRP laminates had approximately 15% (673.85 MPa to 773.76 MPa) over control CFRP laminates. The improvement was caused by that the CNFs thread through carbon fiber arrays along the z-direction in a zigzag pattern and prevent the carbon fiber buckling under longitudinal compressive loads, which is the prime reason for composite failure under compression. The CNF z-threads create a network of mechanically interlocked reinforced fibers that have the capability to incorporate support against interlaminar and intralaminar carbon fiber buckling, ultimately enhancing the longitudinal compressive strength of composites.

In this study, ZT-CFRP laminates were printed using the novel Magnetic Compaction Force Assisted-Additive Manufacturing (MCFA-AM) method [7]. Figure 1 displays a schematic of the novel MCFA-AM printing head and an initial development flowchart. This method uses a compaction force generated by a magnetic field emitter and the backing article attracted by the emitter to rapidly print, compact, and support continuous carbon fiber reinforced polymers (C-CFRP) parts in free space, thus eliminating the need for a mold assembly. This allows for the MCFA-AM method to have a shorter preparation time and negligible size constraints when compared to traditional processes like OOA-VBO. Furthermore, the magnetic compaction force helps reduce the void and defects in the printed CFRP parts. Compared with many mainstream composite additive manufacturing methods that usually manufacturing CFRP parts with excessive voids and defects between layers of filaments, the MCFA-AM has been proven with a great effectiveness in reducing the voids and enhancing the interlaminar shear strength [8] that is comparable to OOA-VBO cured CFRP parts. This paper will study the feasibility and the longitudinal compressive strength improvement if the advanced ZT-CFRP prepreg can be used as the filament for the novel MCFA-AM 3D-printing method.

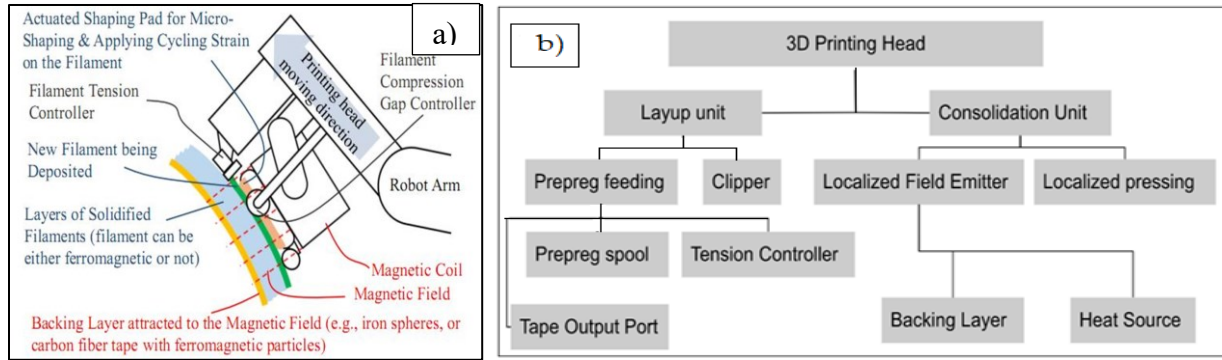


Figure 1: (a) The novel 3D printing head for the patented MCFA-AM method [7], and (b) the block diagram displaying the main components of printing head in its early development stage and their connections under a modularized system construction map.

Over the past few decades, numerous studies have been performed to investigate the influence of various types of nanofillers as reinforcements into composites with a view to attaining better mechanical and electrical properties. CNFs have excellent mechanical strength with the value of the Young's modulus being around 600 GPa and a tensile strength of about 7 GPa [9]. The Young's modulus for CNF is higher than that of steel which is only around 200 GPa. Liu et al. [10] reinforced the matrix with halloysite, and nanosilica to evaluate how different filler materials at certain ratios affect the flexural as well as compressive properties of the composite. A vacuum assisted resin infusion molding (VARIM) method was used to manufacture the control sample to run comparison with other samples reinforced with different kinds of nanofillers, and unidirectional T300 carbon fiber was used for all the laminates. The matrix had the aforementioned nanofillers at a varied concentration between 1-20wt%, and piperidine (from Sigma-Aldrich) as a hardener and Araldite-F from (Huntsman company) as epoxy resin. The testing results revealed that liquid rubber nanofiller had negligible effect on the flexural and compressive properties, however, halloysite as well as nanosilica imposed significant influence on the resin matrix ultimately enhancing the properties by a considerable extent.

One of the notable studies on using CNFs as nanofillers and their effects on both mechanical and electrical properties was performed by Scruggs et al. [11]. They found the through thickness thermal conductivity of CFRP laminates manufactured with AS4 carbon fiber had the conductivity increased from 1.31 W/m-K to 9.85 W/m-K using just 1.0wt% CNF z-threads in the resin. The increase in thermal conductivity allowed the ZT-CFRP laminates to provide better thermal image transparency over that of control CFRP laminates. The performance of these laminates relied a lot on the proper dispersion of the CNFs in the resin blend which ensured well stitching of the CNF z-threads through the entire carbon fiber array. Moreover, a modified resin blend was prepared dispersing both 5wt% and 10wt% CNFs in EPIKOTE 827 resin by Iwahori et al. [12] to impregnate plain weave TORAYCA C6343 fabric. They were able to increase the strength by about 15% when using a hot press method to cure the composite. Zhou et al. [13] used vacuum-assisted resin infusion molding process (VARTIM) method to manufacture satin weave carbon/epoxy composite imparted with CNFs. To modify the epoxy resin, 2wt% CNFs were used for improving the matrix dominated properties of the aforementioned composite. The compressive strength achieved was found to have increased from 292 MPa to 350 MPa with a fiber volume fraction of 56%. Microscopic analysis revealed instances of crack bridging and diminished crack openings that were induced by the 2wt% CNF modified matrix resin addition.

A Resin Film Infusion (RFI) method was used by Anand et al. [14] with randomly aligned multiwalled carbon nanotubes (MWCNTs) well dispersed in an epoxy matrix to enhance different properties of unidirectional E-glass composites. The compressive strength achieved an improvement from 620 MPa to 770 MPa (~24%) for the MWCNT modified samples in comparison to control E-glass samples. Another study by Sharma and Lakkad [15] showed a thermal Chemical Vapor Deposition (CVP) process to grow MWCNTs on the carbon fabric surface at 700 °C. An unmodified control sample was also manufactured following similar thermal treatment and compression die molding methods. The compressive strength displayed an improvement of ~67% in the transverse direction and 4% in the longitudinal direction over the control samples. Taylor et al. [16] ran single lap shear tests on two steel plates single-lap bonded by z-aligned or unaligned CNFs modified epoxy to determine whether the z-alignment is helpful for carry shear-stress at the bond-line. Samples bonded with z-aligned CNFs modified epoxy had a shear strength value around 4.908 MPa while those with unaligned CNFs had a shear strength value around 6.551 MPa; both had noticeable improvement against the control sample using pure epoxy as the bond-line and achieved mean shear strength of 3.772 MPa. It was hypothesized that shear stress at the adhesive layer has its principal direction in 45° angle thus the unaligned CNF modified epoxy adhesive could perform more effectively to carry the shear stress by the CNFs at the bond-line between two steel plates.

2. EXPERIMENTATION

2.1 Materials

The ZT-CFRP prepreg tapes to be used as the feedstock filament for the MCFA-AM 3D-printing experiment were made with unidirectional (UD) HexTow™ AS4 carbon fiber fabric (1.79 g/cm³ fiber density, 190 g/m² areal weight, and 3k tow size). The PR-24-LD-HHT CNFs [17] were from Pyrograf Products, Inc. and provided by Applied Sciences, Inc. The resin blend was made from EPON 862, purchased from Miller Stephenson Chemical Co., Inc., and Araldite LY 3031 (provided by Huntsman Corp.), at a ratio of 2:1 respectively. In order to assist the CNFs disperse well within the matrix, Disperbyk-191 and Disperbyk-192 surfactants, provided by BYK USA, were mixed into the resin blend [18, 19]. Aradur 3032 (provided by Huntsman Corp.) was used as the matrix curing agent at a ratio of 100:11 (resin blend: curing agent) that initiates its cure cycle at 140 °C.

2.2 longitudinal Compression Strength Testing Method

The longitudinal compression strength test followed the procedure from modified ASTM D695 (i.e., SRM 1R-94 [20]: Compression properties of oriented fiber-resin composites). SRM (SACMA Recommended Methods) were developed by SACMA (Suppliers of Advanced Composite Materials Association). An anti-buckling fixture was prepared following instructions from the SACMA standard to hold the samples in place. A TINIUS OLSEN Super “L” Universal Testing Machine with a 12000 lbf (53379 N) load cell and crosshead loading rate at 1.0 mm/min was used to test 3 specimens for each different type of laminate. The top edges of the sample specimens were sanded flat to ensure uniform distribution of the compression load and accurate loading alignment to avoid any eccentric strain or buckling. Depictions and photographs of the testing setup are shown in Figure 2 below.

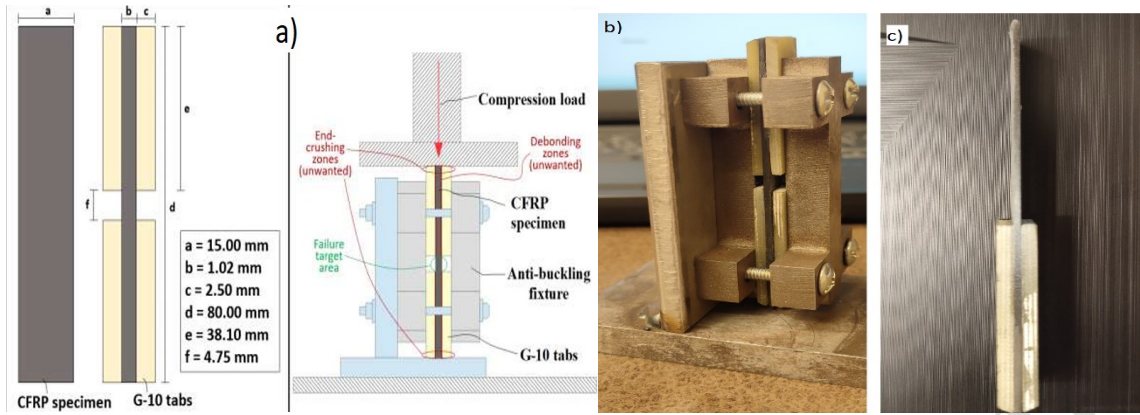


Figure 2: a) Specimen dimension and Anti-buckling testing setup, b) anti-buckling fixture, c) sample specimen.

2.3 Fast Curing ZT-CFRP Prepreg and Its Laminate Printed Using MCFA-AM Method

In order to thread the CNFs into the carbon fiber fabric along the z-direction, the patented Radial Flow Alignment (RFA) technique [21] was implemented in this study. The converging radial flow rheology caused the CNFs to be stretched, aligned, and threaded through the carbon fabric [21]. To prepare the fast-curing CNF/epoxy blend, following the process described in [7] to disperse CNFs into the Epon 862 resin along with BYK191 and 192 by high-shear mixing and sonication, then one can mix the Araldite LY 3031 epoxy and Aradur 3032 curing agent into the solution to obtain the fast-curing CNF/epoxy blend. Inside a fume hood, the mixture was high shear mixed (HSM) at around 300 RPM for an hour, alternating directions every 30 minutes. Sonication was carried out at 90 °C shutdown temperature for an hour. After both processes, a quality control sample from the mixture was observed under microscopic analysis to ensure there are no agglomerates of CNFs in the resin blend. Immediately after adding the curing agent into the well dispersed fast curing CNF/resin blend, the resin beaker was placed in a 10°C ice-water bath to allow for enough time to perform the entire RFA process while maintaining an optimal matrix viscosity. Figure 3 displays a schematic of the RFA process [7] where a carbon fiber tape was wrapped around a hollow perforated tube connected to a vacuum pump; the unique setting created the converging radial flow of the CNF/resin blend and threaded the CNFs into the carbon fiber fabric tape to finally obtain the fully impregnated ZT-CFRP prepregs tape.

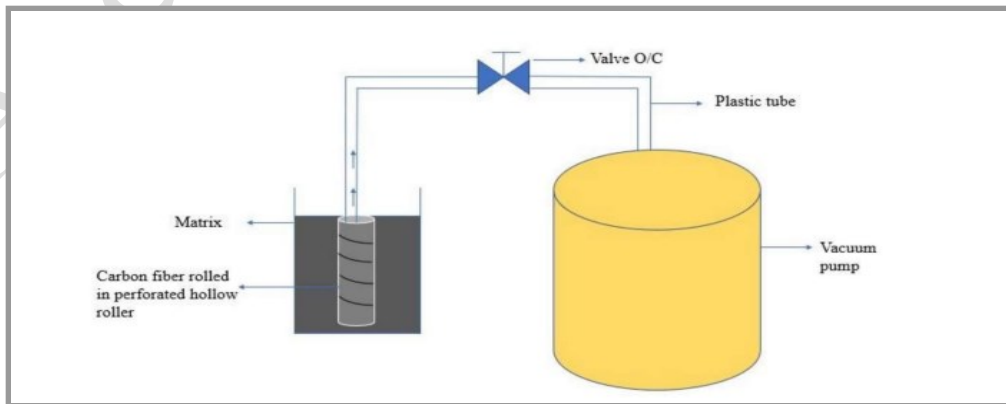


Figure 3: Radial flow alignment (RFA) process to manufacture the ZT-CFRP prepreg [7].

The ZT-CFRP laminate was printed using a custom-made robotic MCFA-AM 3D printer. A printhead designed based on the novel MCFA-AM method was mounted on a 6-DOF robotic arm (Motoman GP 7 Robot Arm from Yaskawa America, Inc.), which was programmed to move the MCFA-AM printhead along pre-determined path for making the laminate samples. A magnetic compaction pressure of 0.5 bar was utilized onto the prepreg and printed the composite laminate by the following steps: (1) anchors one end of a ply of ZT-CFRP prepreg tape and uses MCFA-AM method/printhead to position, compact, and cure (solidified) it in free space, (2) uses the MCFA-AM printhead to lay down, compact, and cure the new layer of ZT-CFRP prepreg tape on top of the aforementioned cured ZT-CFRP layer, (3) repeats step 2 till reaching desired layers of CFRP laminate, and finally (4) detaches the cured/solidified ZT-CFRP part from the anchoring fixture. A heat lamp was used to induce the curing temperature at the fast-curing ZT-CFRP prepreg tape at 140 °C and was fixed in place pointing to the compaction spot where the magnetic compaction force inserting on the prepreg. Before the longitudinal compressive test was performed on the ZT-CFRP laminate, it was subjected to 4 hours of post-curing to ensure full-curing of the resin. It is noteworthy that this robotic MCFA-AM printer design can also work for thermoplastic CFRP tapes.

Figure 4 shows a backing article attracted at the bottom of the printing head by a magnetic field emitter which held the prepreg suspended in free air while it was compressed between a printing press element and the backing article. The prepreg was clamped/anchored on one end while the other end was hand fed during the process (new prepreg filament feeding module will be developed and added on the printhead in the future). Figure 5 displays a zoomed in image that shows the backing article and the spot where it was clamped. The printhead traversed the length of the prepreg from the anchored end to the free end while the tapes were compacted and cured simultaneously.



Figure 4: In this under-development robot-arm driven MCFA-AM printer, A carbon fiber tape is being hand-fed and held by a backing article (cylinder) attracted by a magnetic field emitter (wrapped with aluminum foil).

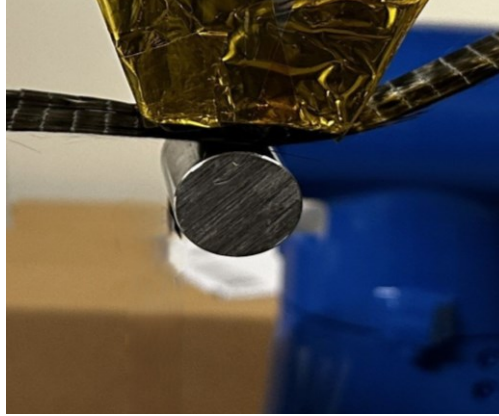


Figure 5: A zoomed in image showing the tape/filament being lifted/compressed by the backing article attracted by the magnetic field emitter.

2.4 No-Pressure CFRP laminate

Making CFRP laminate, cured under zero compaction pressure, to simulate the ‘fusion force only’ scenario when depositing and curing multiple plies of CFRP prepreg together, there was neither any magnetic compaction force nor any vacuum pressure applied onto the prepreps. Instead, they were gently pressed by a roller to set each lamina straight on the stack of prepreps while at the same time being heated by a heat gun at 140 °C to ensure enough curing. To ensure full cure on the resin before the longitudinal compression test, this sample also underwent 4 hours of post-cure. Figure 6 shows a cross section cut on the sideline of the no pressure CFRP laminate.

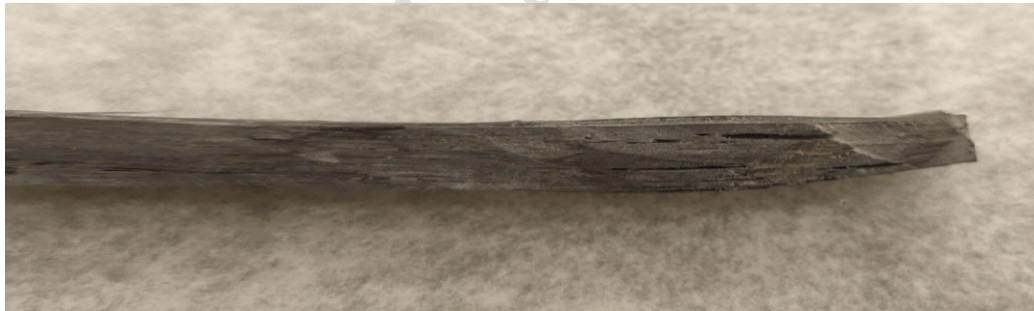


Figure 6: Cross section cut of the no pressure CFRP laminate.

3. RESULTS

A high precision scale and caliper were used to measure the mass and volume respectively to determine the density of the composite. If the effects of void content are considered negligible, FVF can be calculated using equation 1.

$$FVF = (No. of plies \times A_w) / (\rho_f \times t_{lam}) \quad [1]$$

where, A_w = Areal weight of fiber in g/cm, t_{lam} = Thickness of laminate in cm, and ρ_f = Density of fiber in g/cm³. Matrix density was calculated using the rule of mixtures with the density of the fiber as 1.79 g/cm³, areal weight as 0.019 g/cm², and laminate thickness to be 1.2 mm. Moreover,

the FVF of a single prepreg to be used for the MCFA-AM study was maintained in such a way that all of them retained 53% FVF by passing the fully impregnated prepreg through a gage-controlled gap to remove the excessive resin and control the final thickness of the prepreg.

The primary reason for a sample undergoing compression load failure is fiber buckling, which is an acceptable mode of failure. Of the unacceptable modes of failure, tab debonding is one of the notable ones. The authors [1] had encountered this kind of failure for their samples as they used EPON 862 epoxy resin as an adhesive. To avoid repeating the same issues, the tabs were bonded with J-B Weld™, a toughened epoxy adhesive, to reinforce the testing sample. The graphs in Figures 7 and 8 respectively display a more elaborate scenario of all the individual sample types and testing order of the specimens for ZT-CFRP (MCFA-AM) laminate and no-pressure CFRP laminate. For the ZT-CFRP laminates (Figure 7), the 1st and 2nd sample underwent compressive failure and the 3rd one had its end crushed when it failed. The failure images of ZT-CFRP (MCFA-AM) laminate samples are shown in figure 9. The maximum amount of compressive load of 633 MPa was sustained by the 3rd sample and from the data points in Figure 7; it can be estimated that it could rise a little more above 633 MPa unless it was affected by end crushing failure.

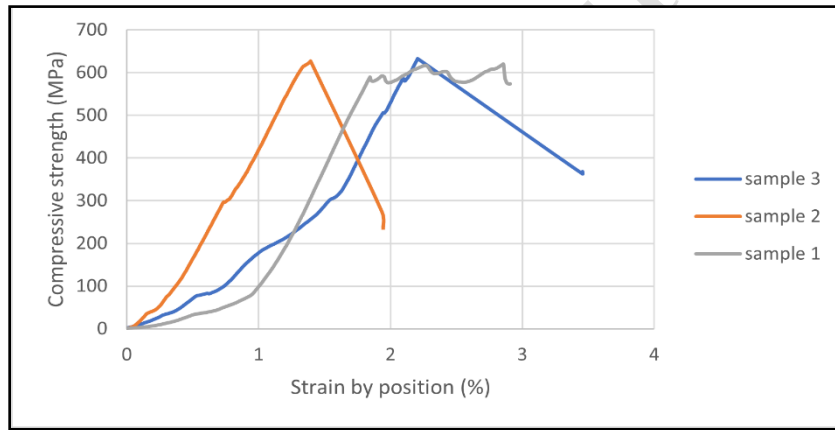


Figure 7: Compressive strength vs. crosshead position for 1.0wt% ZT-CFRP laminate.

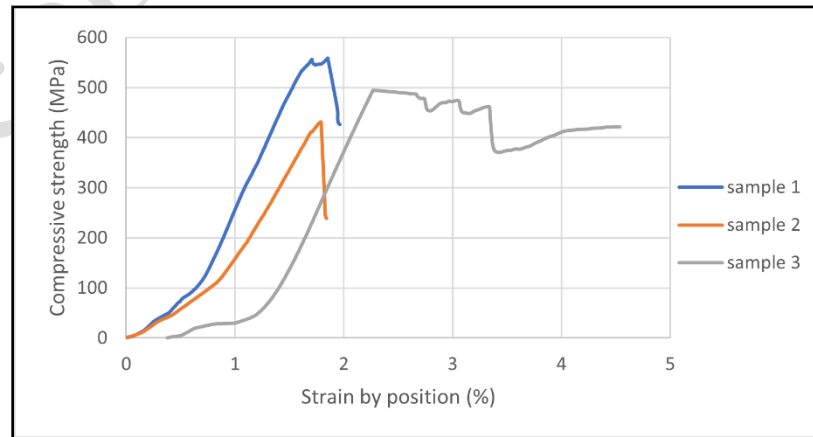


Figure 8: Compressive strength vs. crosshead position for No Pressure CFRP laminate.

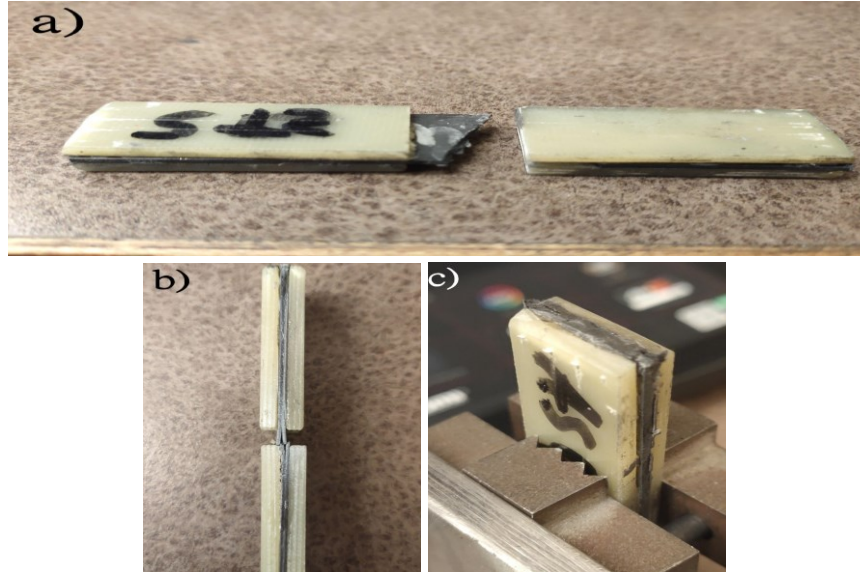
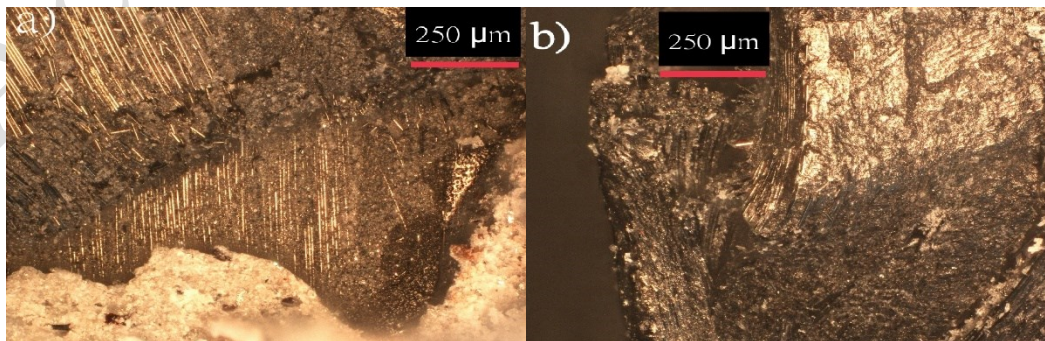


Figure 9: a) Sample 1 failure crack at 45°, b) Sample 2 fiber compressed into crack, c) Sample 3 crushed end with smaller cracks.

3.1 Microscopic morphology of specimens' failure

A microscopy analysis was performed on the longitudinal compressive strength failures to gain a better understanding of the CNF roles during crack propagation and fiber buckling, to compare ZT-CFRP samples with the control CFRP ones. This analysis was undertaken with a view to clarifying the role of the CNFs during compressive failure. The microscope used was Nikon Eclipse LV150 (Digital Sight DS-Fi1) optical microscope equipped with an extended depth of focus (EDF) module.

ZT-CFRP (MCFA-AM) sample 1 underwent compressive failure mode where the crack occurred at an angle of 45° at the neck region. From Figure 7, it can be observed that the curve for sample 2 remains stable at about 600 MPa with slight ups and downs and right before reaching ~627 MPa and failing completely. This was indicative of buckling after roughly 600 MPa. The buckling, cracks and pulled off CNFs for sample 1 are illustrated in Figure 10. As for sample 2, Figure 11 displays a broken top fiber trying to push into the crack on account of the compressive load and a 1000x picture with CNFs along the z-direction in it.



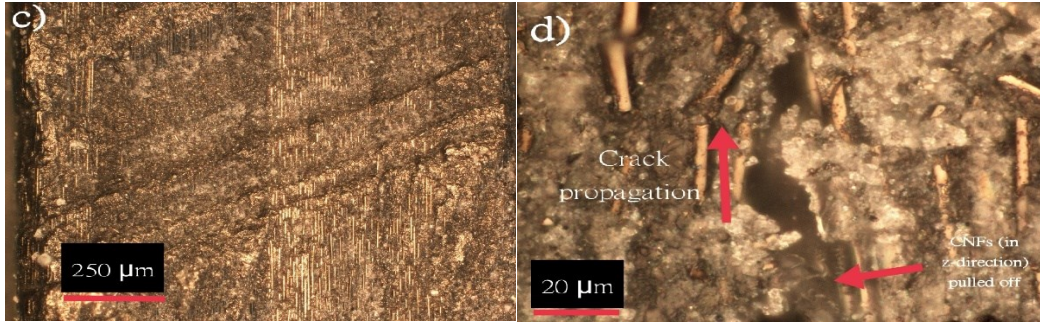


Figure 10: Microscope pictures of ZT-CFRP (MCFA-AM) sample 1. a) (100x) 45° angle crack, b) (100x) crack width (Top view) ~250 μm , c) (100x) slight 45° buckling, d) (1000x) pulled off CNFs in the crack region.

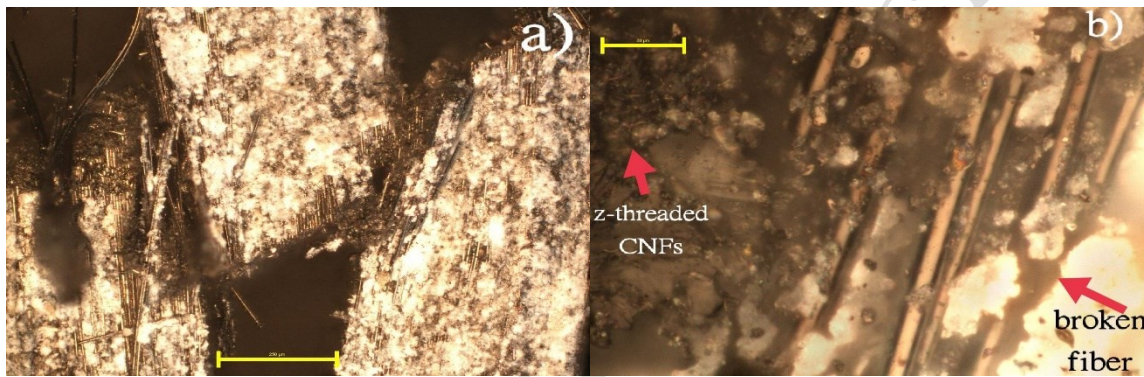


Figure 11: Microscope pictures of ZT-CFRP (MCFA-AM) sample 2. a) (100x) top fiber crushing its way into the crack between bottom fibers due to compression, b) (1000x) visible CNFs stitched in the z-direction and deforming in the path of compression near the bottom left.

3.2 Discussion

The longitudinal compressive strength value of control CFRP samples (673.85 MPa) had been set as the benchmark for the comparison. The strength values of the Control CFRP (OOA-VBO), ZT-CFRP (OOA-VBO), Unaligned CNF-modified CFRP, all cured by OOA-VBO methods under 1-bar compaction pressure, are extracted from the paper already published [1] in SAMPE 2019 conference and compared with the values from the no pressure CFRP and MCFA-AM printed ZT-CFRP specimens tested in this paper. Table 1 displays the longitudinal compressive strength values and other necessary data for all the samples used to run comparison among one another. The COV for no pressure CFRP samples is 13% as their compressive strength values were not consistent. This happened because of a considerable amount of air traps as well as different sizes of voids that were noticeable in the laminate after curing since it did not undergo any compaction pressure while printing. On the contrary, the ZT-CFRP (MCFA-AM) samples have an excellent COV of 1% that establishes the consistency of their longitudinal compressive strength values as well as the performance and reliability as a composite part. The laminates produced through OOA-VBO method [1] experienced a vacuum pressure of 1 bar that enabled the samples to endure higher compressive load and eventually fail at an average of ~673.85 MPa pressure. On the contrary, the MCFA-AM printed ZT-CFRP laminates underwent half of that pressure (0.5 bar pressure) and could still withstand

a compressive load of about 626.68 MPa on average which is reasonably close to the values of that of OOA-VBO samples. The reasons behind the low values of compressive strength are the lower fiber volume fraction (FVF of 57% (control CFRP) vs 53% (ZT-CFRP by MCFA-AM)) and possibly the less amount of compaction pressure that affected their internal nanostructures. Note that the FVF of the MCFA-AM is primarily controlled by the prepreg thickness and can be increased during the prepreg production process. The CNF z-threads provide better stiffness to carbon fiber prepreps that ultimately reduce instability as well as the adversary impact of voids and defective areas inside the composite laminates.

Table 1: Longitudinal compressive strength results for Control CFRP (OOA-VBO) [1], ZT-CFRP (OOA-VBO) [1], Unaligned CNF-modified CFRP (OOA-VBO) [1], ZT-CFRP samples, and No Pressure CFRP samples.

Sample type	Compaction Pressure	Area (mm ²)	Ultimate Force (N)	Ultimate strain (%)	FVF (%)	Longitudinal Compressive Strength (MPa)	COV (%)	Relative Improvement of Compressive Strength w.r.t. Control CFRP (%)
1 wt% ZT-CFRP (OOA-VBO) [1]	1 bar	14.76	11401.22	1.19	54±1	773.76	9.33	+14.83
Control CFRP (OOA-VBO) [1]	1 bar	15.34	10337.7	1.18	57±1	673.85	9.41	N/A
1 wt% UA CFRP (OOA-VBO) [1]	1 bar	15.27	9462.53	1.32	53±1	619.84	9.56	- 8.02
No Pressure CFRP (MCFA-AM)	0 bar	17.19	8577.83	1.04	53±1	496.87	13	-26.48
1 wt% ZT-CFRP (MCFA-AM)	0.5 bar	16.44	10307.75	1.06	53±1	626.68	1	-7%

4. CONCLUSIONS

It has already been established that ZT-CFRP manufactured through OOA-VBO has an improvement of about 15% over control CFRP in terms of compressive strength [1]. As well as CNF Z-threads assist to enhance the longitudinal compressive strength of the laminate by working as both interlaminar and intralaminar reinforcements to the AS4 fiber yarns [1]. As the graph in Figure 12 illustrates, the no pressure CFRP samples (as the typical filament deposition process), printed at 0 bar vacuum pressure, have about 496.87 MPa compressive strength whereas the control CFRP (OOA-VBO) samples, manufactured at 1 bar vacuum pressure, have about 673.85 MPa. The ZT-CFRP laminates manufactured via the MCFA-AM method in this study had a compaction pressure (0.5 bar) that is half of that of CFRP (OOA-VBO) laminates. The longitudinal compressive strength for the preliminary robotic MCFA-AM printed ZT-CFRP at 0.5 bar processing compaction pressure is very comparable to the

CFRP manufactured using the full vacuumed (1 bar) OOA-VBO method and has only 7% reduction in the longitudinal compressive strength.

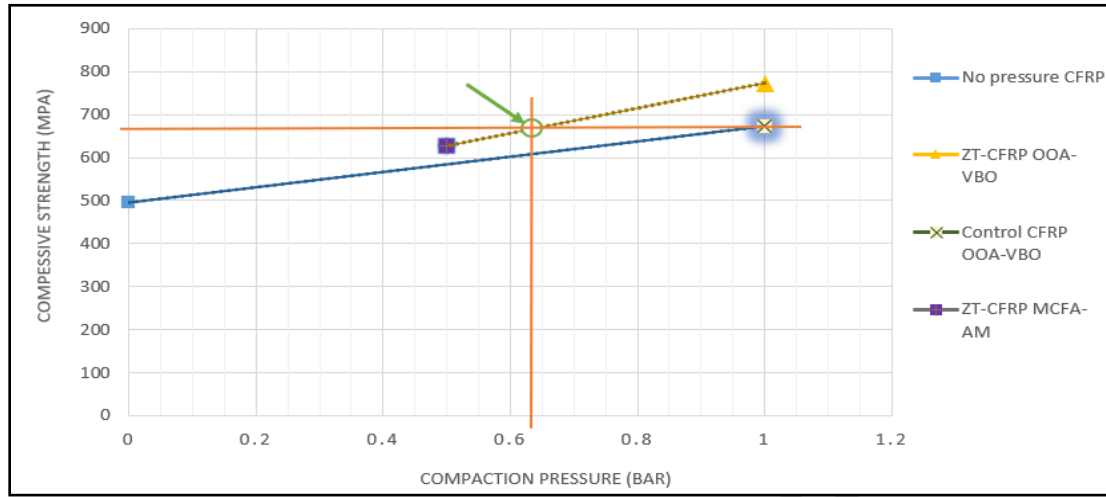


Figure 12: Comparison among all different CFRP samples to highlight a prediction of desired compaction pressure during a MCFA-AM 3D printing process setting.

Additionally, the maximum strength is attributed to the ZT-CFRP (OOA-VBO) samples which is about 773.76 MPa. The highlighted (green arrow) point on the graph is located between these two different ZT-CFRP samples manufactured via MCFA-AM (0.5 bar compaction pressure) and OOA-VBO (1 bar compaction pressure) methods, respectively. This highlighted point suggests the longitudinal compressive strength of 673 MPa can be achieved at approximately 0.62 bar pressure for the MCFA-AM method when using the ZT-CFRP prepreg. Further improvement on the robotic MCFA-AM 3D printer's magnetic compaction pressure up to approximately 0.62 bar or more could yield the ZT-CFRP parts with a longitudinal compressive strength equivalent or beyond the control CFRP parts cured by the benchmark OOA-VBO method. As the compaction pressure of the MCFA-AM printhead is controlled by the magnetic field emitter, the compaction pressure can be adjusted and increased in the future study to yield stronger CFRP and ZT-CFRP parts.

5. ACKNOWLEDGMENTS

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7. APPENDIX

Table A-1: Compressive strength data for 1.0wt% MCFA-AM (0.5-bar) ZT-CFRP laminates.

Specimen order	Length (mm)	Width (mm)	Thickness (mm)	Area (mm ²)	Ultimate Force (N)	Ultimate Strain (%)	Compressive strength (MPa)	Failure mode	Compressive Strength Improvement w.r.t. Control (%)
Sample 1	80	15.1	1.09	16.46	10208.61	1.07	620.245	Compressive failure	
Sample 2	80.02	15.06	1.12	16.86	10572.02	1.04	626.78	Compressive failure	
Sample 3	79.60	15.1	1.06	16	10142.63	1.02	633.007	End crushed	
Mean	79.87	15.08	1.09	16.44	10307.75	1.06	626.677		+7%
STDEV	0.23	.02	.03	.43	231.21	.03	6.38		
Maximum	80.02	15.1	1.12	16.86	10572.02	1.07	633.01		
Minimum	79.6	15.06	1.06	16	10142.63	1.02	620.245		
COV (%)	0%	0%	3%	3%	2%	1%	1%		

Table A-2: Compressive strength data for No Pressure CFRP laminates.

Specimen	Length (mm)	Width (mm)	Thickness (mm)	Area (mm ²)	Ultimate force (N)	Ultimate strain (%)	Ultimate strength (MPa)	Failure mode	Compressive Strength Improvement w.r.t. Control (%)
Sample 1	80	15.06	1.09	16.41	9344.10	1.02	559.40	Compressive failure	
Sample 2	80	15.12	1.15	17.38	7502.23	1.018	431.65	Compressive failure	
Sample 3	80.01	15.21	1.17	17.79	8887.17	1.06	499.56	Tab debonding and end crushing	
Mean	80	15.13	1.13	17.19	8577.83	1.04	496.87		-26.48%
STDEV	.005	0.26	0.04	0.71	959.11	.02	63.92		
Maximum	80.01	15.21	1.09	17.79	9344.1	1.06	559.4		
Minimum	80	15.06	1.17	16.41	7502.23	1.018	431.65		
COV (%)	0%	2%	4%	4%	11%	2%	13%		