NANOFIBER Z-THREADED CFRP AND THE MULTIFUNCTIONALITY FOR ADVANCED AIR MOBILITY

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Abstract

Carbon fiber reinforced polymer (CFRP) is one of promising lightweight materials for advanced air mobility (and electrical vehicles) due to the high strength, low density, and corrosion resistance. On the other hand, CFRP is more expensive than many lightweight alloys, difficult to join, less fire-resistant, lower conductivities in thermal and electrical energy, more sensitive in processing defects, and more difficult to inspect its structural damages. To improve the multifunctionality desired by advanced air mobility, CFRP could be modified with nanoparticles. Nanofiber z-threaded CFRP (ZT-CFRP) technology utilizes millions of long carbon nanofibers to z-directionally thread through all carbon fibers in per square-centimeters of ZT-CFRP prepreg. The ZT-CFRP enhanced the mechanical properties, thermal conductivity, and electrical conductivity. The unique 3D-multicscaled fiber-reinforced microstructure also provide additional performance such as enhanced resistance against the property degradation caused by void, enhanced flame-retardance, improved adhesive-joint (i.e., bond line) strength, and enhanced thermal infrared damage/defect evaluation resolutions. This paper will overview the ZT-CFRP performances along with the state of ZT-CFRP prepreg process development including the scaled up roll-to-roll hot-melt manufacturing process of the ZT-CFRP prepreg. Its potentially useful multifunctional attributes for advanced air mobility will also be discussed in this paper.

Introduction

Advanced air mobility (AAM) presents a great alternative transportation method than ground transportation and the existing air transportation such as airliners or private small planes. For example, electric vertical takeoff and landing (eVTOL) aircrafts are a type of representative and promising AAM vehicles. Different than traditional air transportation vehicles, AAM vehicles usually are flying a lower attitude for a shorter range and a smaller number of passengers, and will need to address cost and efficiency and to be produced with larger quantity. Furthermore, battery-powered electric vehicles are a popular power solution for AAM. As the battery is a main design factor for operating range and performance for AAM vehicles, the weight saving of the airframe becomes very crucial for AAM. Therefore, lightweight materials such as composite materials are playing important role for the performance of AAM vehicles. According to [1], eVTOLs could have about 70% by weight of the structure made of composite materials; such a number is significantly higher than Boeing 787 of using composites in about 50% by weight of the structure. For eVTOLs, composites can be found in fuselage, wings, flight control surfaces, beams, seating structures, battery boxes and racks, rotor-blades, nacelle assembly, and other parts such as clips, brackets, etc. [1]; and among all the composites used 75-80% will in structural and propulsion systems, 12-14% will be in interior components, and 8-12% will be for the battery and avionics systems and other small applications. About 90% of the composites are reinforced with carbon fibers and the remaining 10% are reinforced by fiberglass. eVTOLs composite parts will need to meet aerospace quality for flight-worthiness but also need to meet the production speed expectation of higher than traditional aircraft but less than automotive industry (e.g., 6000-8000+ vehicles annual production). Thermoset carbon fiber reinforced polymer (CFRP) is heavily

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used in eVTOLs, due to the maturity and readiness of aerospace grade thermoset CFRP products already used by current aerospace industry. But Thermoplastic CFRP can be used for smaller parts and the adoption could be ramping up for the recycling advantages although the production quality, part size limitation, and cost are of disadvantages compared with thermoset CFRP.

While AAM vehicles are using existing aerospace grade thermoset CFRP materials from currently aerospace industry, mainly due to the flight-worthiness certification readiness; however, for the long run, one could ask the question that "would the matured thermoset CFRP materials used by current aerospace industry be optimal for the AAM industry?" One can argue that current aerospace grade composite materials have been developed and optimized for large commercial airliners with different parameters in terms of design, performance, part-size, cost, and production speed, maintenance, etc., may not be optimal for the AAM vehicles or even the fleet operation concept. Therefore, for AAM vehicles, newer thermoset CFRP composite materials and/or thermoplastic CFRP composite materials may need to be developed to optimally fit for the AAM's ecosystems in the future.

Multifunctional Carbon Nanofibers Z-Threaded CFRP (ZT-CFRP) Prepreg – Concept and Experimental Data of Properties and Performance

Since AAM vehicles are low attitude and short range small aircraft to be produced with faster assembling and larger volume than traditional commercial airliners, it is desired that the carbon fiber composites for AAM can be easier to assemble, and with additional multifunctionality to reduce the complexity of the aerostructure and hopefully the costs of manufacturing, maintenance, and operation. For example, traditional CFRP composites need to need to bond a metal mesh layer and a fiberglass insulation layer outside of CFRP to protect the aircraft from lightning strike, use flame retardant chemicals to enhance the fire safety, need to consider the adhesive bonding performance, the rivet-joint stress-concentration and the matrix sensitive properties to cause premature delamination, etc. These factors can cause weight increase and add costs and complexity in manufacturing, assembly, maintenance, repair, and operation, etc. Many of these concerns are caused by the polymer matrix of a CFRP. Therefore, the improvement of the polymer matrix system or the polymer matrix's roles in connecting the carbon fibers together and protecting the carbon fibers in the CFRP could provide the cures or mitigation of the pain points of using exiting airliners' CFRP in AAM vehicles.

Through the past two decades since the discovery of carbon nanotubes, many nanocomposite research results shows that nanoparticles such as carbon nanotubes (CNTs) and carbon nanofibers (CNFs), due to their small diameters, long aspect ratios, low densities, and excellent mechanical and electrical properties, if well-dispersed in the polymer matrix, can be added in CFRP to improve the mechanical and electrical properties [2,3,4,5]. However, the significant scaling-up issues and values of translating such batch-scale lab-results to CFRP industry is strongly hindered by the manufacturing and performance improvement uncertainty associated with the CNTs or CNFs' alignment control and dispersion control inside the CFRP composites, the cost concerns, the CNT/CNF supply chain/quality uncertainty, and the proper form of CFRP products can be easy and ready to use for manufacturing into CFRP parts for the users industries such as sporting goods, aerospace, defense, automotive, and AAM industries.

One of common forms of CFRP products is the prepreg, which is commonly used in sporting goods, automotive, and aerospace sectors. The nanofiber z-threaded CFRP (ZT-CFRP) is a patented composite technology [6,7,8] that is available in the form of prepreg. Well-dispersed long nanofibers are aligned and threading through the porous bed of carbon fibers (such as carbon fiber fabric or carbon fiber tape) along the thickness direction (i.e., z-direction) driven by electrical field and/or rheological methods. Figure 1 shows some illustrations and microscope pictures to explain the microstructure of a ZT-CFRP prepreg. As shown in Figure 1, the long CNFs thread through the gaps between individual carbon fibers in a zigzag pattern due to the tightly packed carbon fiber porous bed, and form a mechanical-interlocking effect. Since CNFs have good mechanical, thermal, and electrical properties, such CNF z-threading can also effectively integrate the CNF's excellent properties with the carbon fiber's properties and create the interesting and synergetic multiscale fiber-reinforcing network. From the microstructure, one can hypothesize the zigzag z-threading mechanism not only enhances the ZT-CFRP composite properties in the z-direction but also enhances the y-directional (i.e., in-plane direction perpendicular to the carbon fiber direction) properties. Furthermore, the z-threading will likely also help stabilize the carbon fiber against fiber micro-buckling when under longitudinal compression (i.e., compression along the carbon fiber direction). In terms of energy aspect, one can expect the ZT-CFRP can dissipate or conduct energy (e.g., mechanical work, electrical current, and heat) through the carbon fiber/CNFs z-threading network more effectively than regular CFRP.

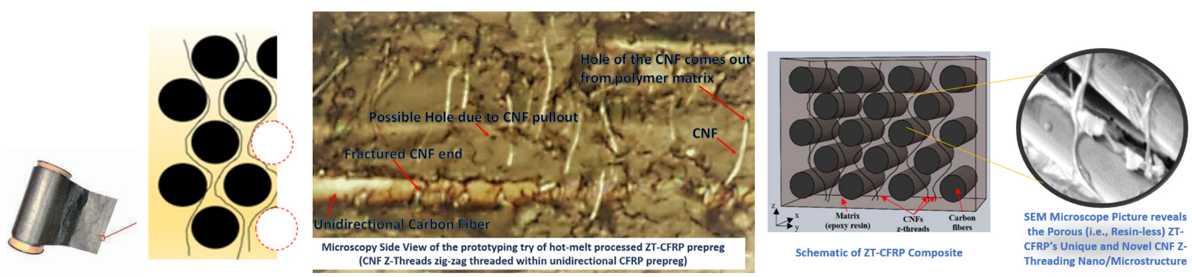


Figure 1: Illustrations and microscope pictures to explain the microstructure of a ZT-CFRP prepreg.

Experimental characterization of some notable matrix sensitive properties of ZT-CFRP previously reported [9-16] are summarized in Table I for understanding the novel material and validating the afore-discussed property improvement hypotheses based on the novel z-threading microstructure. In terms of mechanical properties, the mode-I delamination toughness, the interlaminar shear strength (ILSS), the longitudinal compressive strength were improved by 29%, 17%, and 14.83%, respectively. The z-directional DC electrical conductivity was improved by 238%, 1508%, and 10050% depending on the CNF concentration and heat-treatment, carbon fiber used, and the ZT-CFRP prepreg manufacturing methods. The z-directional thermal conductivity has been improved by 653%. Besides the improvements in all tested matrix sensitive properties in terms of their mean values, it was also found ZT-CFRP specimens consistently had smaller coefficient of variation (C.O.V.) in all types of properties tested. The possible reason could be that for all the matrix-sensitive properties, the polymer matrix filled into the gap between carbon fibers was more difficult to control in terms of gap size, relative locations, and voids; therefore, when CNFs z-threaded between the carbon fibers, the influence of the much weaker and less conductive polymer matrix was reduced and hence the properties became more consistent among the specimens. From Table I, one can understand the ZT-CFRP provides better and more reliable matrix-sensitive properties, which could significantly help the engineers to design lighter and more reliable CFRP parts for AAM aircrafts. Such reliability improvements and mean value improvements in matrix-sensitive properties could allow engineers to design lighter composite parts.

Table I: Some matrix sensitive properties of ZT-CFRP laminates [9-16]

MATERIAL PROPERTY	CNF WT%	CNF TYPE	CF TYPE	FIBER AREAL WEIGHT	SURFACTANT	RESIN TYPE	FVF	MANUFACTURING METHOD	CONTROL CFRP	ZT-CFRP	IMPROVEMENT
Mode-I Delamination [9]	0.1-0.3wt%	PR-24-XT-PS	T300 plain weave (Toray)	203 g/m^2	CNF Surface Oxidation Treatment	EPON 862/ Epikure-W	53%	Resin-flow transfer (sponge)	305 J/m^2	397 J/m^2	+29%
Through-Thickness DC Elec. Conductivity [10]	0.1wt%	PR-24-XT-PS	T700 UD (Toray)	680 g/m^2	CNF Surface Oxidation Treatment	EPON 862/ Epikure-W	64%	Resin-flow transfer (sponge)	1.58 S/m	5.35 S/m	+238%
Through-Thickness DC Elec. Conductivity [11]	1.0wt%	PR-24-XT-HHT	AS4 UD (Hexcel)	190 g/m^2	Disperbyk 191 & 192	EPON 862/ Epikure-W	72%	Resin-flow transfer (sponge)	0.26 S/m	4.18 S/m	+1,508%
Through-Thickness DC Elec. Conductivity [12]	>1.0wt %	PR-24-XT-HHT	AS4 UD (Hexcel)	190 g/m^2	Disperbyk 191 & 192	EPON 862/ Epikure-W	NR	Radial flow-alignment	0.16 S/m	16.24 S/m	+10,050%
Through-Thickness Thermal Conductivity [13]	1.0wt%	PR-24-XT-HHT	AS4 UD (Hexcel)	190 g/m^2	Disperbyk 191 & 192	EPON 862/ Epikure-W	72%	Resin-flow transfer (sponge)	1.31 W/m-K	9.85 W/m-K	+653%
ILSS [14, 15]	1.0wt%	PR-24-XT-HHT	AS4 UD (Hexcel)	190 g/m^2	Disperbyk 191 & 192	EPON 862/ Epikure-W	60%	Resin-flow transfer (resin film)	64.89 MPa	75.92 MPa	+17%
Longitudinal Compressive Strength [16]	1.0wt%	PR-24-XT-HHT	AS4 UD (Hexcel)	190 g/m^2	Disperbyk 191 & 192	EPON 862/ Epikure-W	54%	Resin-flow transfer (resin film)	673.85 MPa	773.76 MPa	+14.83%

NR: not recorded; FVF: Carbon fiber volume fraction in CFRP; UD: Unidirectional; PS: Pyrolytically stripped carbon nanofibers; HHT: High-heat treated (up to 3000°C) carbon nanofibers; XT: Debulked form.

While the matrix sensitive properties were improved, there could be some other related multifunctional performance also be enhanced. For example, the +653% higher thermal conductivity in the z-directional can help the thermal infrared signal being transmitted with less distortion through the thickness of a ZT-CFRP laminate; this can be useful to enhance the thermography non-destructive evaluation (NDE). Figure 2 showed that the thermal image of a heated copper triangle can be clearly observed by a thermal infrared camera through a unidirectional ZT-CFRP laminate but not through a regular unidirectional CFRP laminate [13]. For the regular unidirectional CFRP, the significantly higher thermal conductivity in the carbon fiber direction (x-direction) and significantly lower z-directional and y-directional thermal conductivities created the non-isotropic heat transfer and distorted the thermal image badly. On the other hand, the ZT-CFRP laminates, due to the highly conductive CNFs zigzag z-threading and interlocking among the carbon fibers, created an isotropic heat transfer and showed thermal image of the triangle faithfully. This performance can help the NDE of composite parts and will find values for assembly inspection, maintenance, and repair of AAM aircrafts.

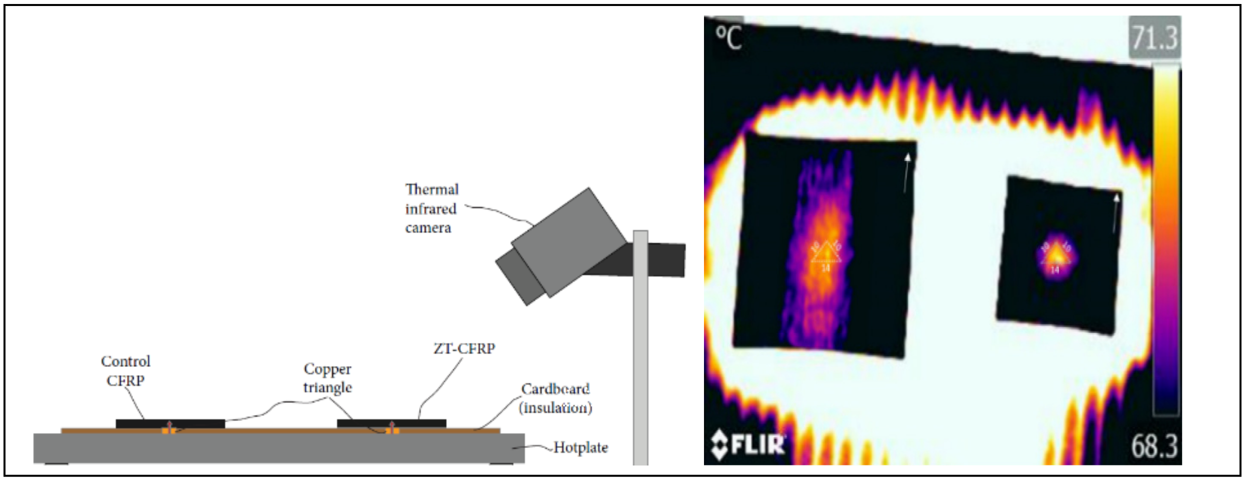
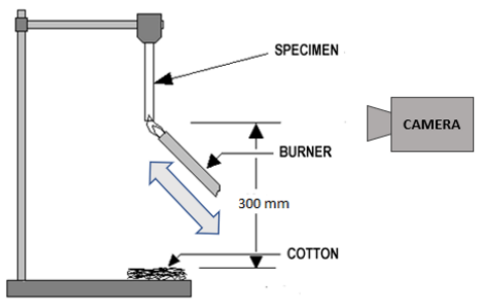


Figure 2: The unidirectional ZT-CFRP laminate, due to the highly conductive CNFs zigzag z-threading among the carbon fibers, created an isotropic heat transfer and faithfully showed thermal image of the heated copper triangle placed under the ZT-CFRP laminate. The unidirectional control CFRP, due to the non-isotropic thermal conductivities, showed significantly distorted thermal image and failed to show the triangle. [13]

The ZT-CFRP's microstructure have also been found to improve the flame-retardance of CFRP panel without using any flame retardant chemical additives [17]. In the study, regular unidirectional CFRP specimens (control samples) and unidirectional ZT-CFRP specimens were subjected to UL-94 vertical flammability test (see Figure 3 for the details and rating criteria). Neither type of the samples contained any flame retardant chemical additives. The UL-94 V testing results are given in Table II. Overall, both types of samples were unrated by UL-94 criteria; however, the ZT-CFRP samples are close to and could meet the V-1 rating if the ZT-CFRP's manufacturing quality could be improved. As ZT-CFRP samples #1, #2, #5, and the set of five specimens results all met the V-1 rating criteria, if the sample #3 and #4 can be improved to have shorter flame extinguishing time (likely through better quality control during the prepreg and laminate manufacturing processes), the unidirectional ZT-CFRP case could enter the V-1 rating without using any other flame-retardant chemicals. None of the unidirectional ZT-CFRP samples had flame spreading, which was great. On the other hand, the regular unidirectional CFRP specimens failed the V-1 & V-2 criteria almost all individual samples (except control sample #4) and the set of five specimens failed the set criteria; furthermore, the control samples presented 60% chance for the flame spreading upward to burn the clamp which held the specimen. Figure 4 shows some pictures taken during the UL-94 experiment, and one can see the flame spreading of a regular unidirectional CFRP specimen and the quick self-extinguishing of a unidirectional ZT-CFRP specimen. Despite the rating, compared with the unidirectional CFRP control case, the unidirectional ZT-CFRP case clearly showed flame self-extinguishing behavior and inhibited flame spreading (upwards and downwards) without using flame retardant chemicals additives. It shortened the flame extinguishing time to 40% of the control CFRP case and fully stopped the flame spreading. The hypotheses for this flammability test finding could be associate with the char retaining capability of ZT-CFRP, the ZT-CFRP's z-threading mechanical interlocking integrity prevented delamination or/and microcrack formation under fire, and the 7 times higher thermal conductivity of the ZT-CFRP helped to quench the composite specimen, etc.. The flame self-extinguishing behavior of ZT-CFRP can help find a novel way to reduce the use of flame-retardant chemicals that are known to be possibly harmful to the health and environment. Furthermore, it may find extreme temperature applications if the matrix system being replaced with a high temperature matrix. The self-extinguishing ability could also be useful to protect the ZT-CFRP structure from lightning strike damage if one considers the ZT-CFRP's higher electrical conductivity and higher thermal conductivity as well. Further research in this direction would be interesting and could be useful for AAM industry.



Burner Fuel: Propane (Flame Temperature ~ 2820 C in oxygen and 1980 C in air, which is high enough to quickly ignite the carbon fibers, CNFs, and the epoxy!)

For each composite specimen:
- Apply flame contact with the specimen for 10 seconds for igniting the specimen, remove the flame immediately after 10 seconds.
- Video record the flame burning till extinguished. Record the duration (t1)
- Apply the second ignition procedure on the same specimen and record the flame burning till extinguished. Record the duration (t2)
- Remove the specimen.

Criteria	V-0	V-1	V-2
Afterflame for each individual specimen (t1 and t2 individually considered)	≤ 10s	≤ 30s	≤ 30s
Total afterflame for a set of specimens (t1 + t2 for all 5 specimens)	≤ 50s	≤ 250s	≤ 250s
Afterflame plus afterglow time for each individual specimen after the second flame application	≤ 30s	≤ 60s	≤ 60s
Afterflame or afterglow of any specimen up to the holding clamp	No	No	No
Cotton indicator ignition	No	No	Yes

Figure 3: UL-94 Vertical Flammability Test Explanation

Table II: Comparison of UL-94 V flammability testing numbers of regular unidirectional CFRP laminate specimens and unidirectional ZT-CFRP laminate specimens [17]

Sample	t1 (s) (≤ 10s? or ≤ 30s?)	t2 (s) (≤ 10s? or ≤ 30s?)	t3 (s)	Burn to Clamp (upward flame spreading)	Cotton Ignition (dripping flame spreading)	Sum (s) (t1+t2+t3) (induvial specimen; ≤ 30s? or ≤ 60s?)	Average (s) t_{avg}	Normalized Average Flame Self-Extinguishing Time based on the Control Samples' average time (%)	Burn to Clamp Chance (%)
Control CFRP									
1	39.5	0	0	N	N	39.5			
2	26.5	89.8	0	Y	N	116.3			
3	0	144.3	0	Y	N	144.3	86.8	100% (Baseline)	60% (Baseline)
4	0	5.5	0	N	N	5.5			
5	5.4	123.2	0	Y	N	128.6			
Set Total	71.4	362.8	0	Y & N	N	434.2 (>250)			
Set Average	14.3	72.6	0	Not OK	OK	86.8			
1wt% CNF ZT-CFRP									
1	17.2	0	0	N	N	17.2			
2	0	0	0	N	N	0			
3	0	35.8	0	N	N	35.8	34.9	40%	0%
4	37.2	54.7	0	N	N	91.6			
5	0	29.7	0	N	N	29.7			
Set Total	54.4	120.2	0	N	N	174.6 (<250)			
Set Average	10.9	24.0	0	OK	OK	34.9			

Color Code of Data: Best sample, Worst sample, **Mid sample (the 3rd ranked of 5 specimens)**

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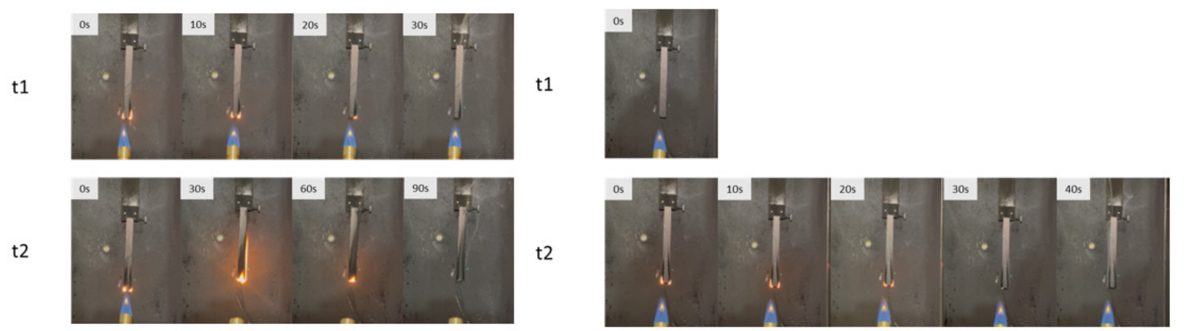

Afterflame (Propane) of Control CFRP sample #2. Afterflame (Propane) of 1wt% CNF ZT-CFRP sample #5

Figure 4: Pictures taken during the UL-94 experiment: the flame spreading of a regular unidirectional CFRP specimen (left) and the quick self-extinguishing of a unidirectional ZT-CFRP specimen (right) [17].

The better mechanical properties of the ZT-CFRP can help the adhesive bond-line for joining CFRP laminates. In a lap-joint specimen of two CFRP panels, as shown in Figure 5, the failure site could be in the adhesive, the CFRP adherend, or/and the bonding interface between the adhesive and adherend (not shown). Therefore, if the adhesive is strong enough and bonds well with the CFRP through the interface, the failure site will be in the CFRP likely through delamination or shear failure or other matrix-sensitive failures. For this reason, it is believed that ZT-CFRP can promote a stronger bond-line than regular CFRP. In a reported study [18], two types of bond-line samples, which had 1wt% CNF being used in the ZT-CFRP laminate or/and the epoxy adhesives, were compared with regular CFRP bonded with neat epoxy adhesive. Compared with the single lap shear strength (tested by ASTM D5868-01 method) of the control case (regular CFRP bonded with neat epoxy adhesive), the results showed that the 1wt% CNF toughened epoxy adhesive improved by 13.8% and the addition of ZT-CRRP improved by 43.8% above the control specimens [18]. As shown in Figure 6, the CNF toughened epoxy adhesive helped to move the failure site from the adhesive into the CFRP adherend. The failure site of the CNF toughened epoxy adhesive bonded ZT-CFRP panel presented a further complex failure scenario including delamination as well as the carbon fiber compressive failure and adhesive film compressive failure along the tensile force direction. Two microscope pictures of the failure sites in ZT-CFRP adherends are also shown the aligned CNFs, which likely enhanced the mechanical load transfer and improved the matrix sensitive properties during the single-lap bond-line test.   .

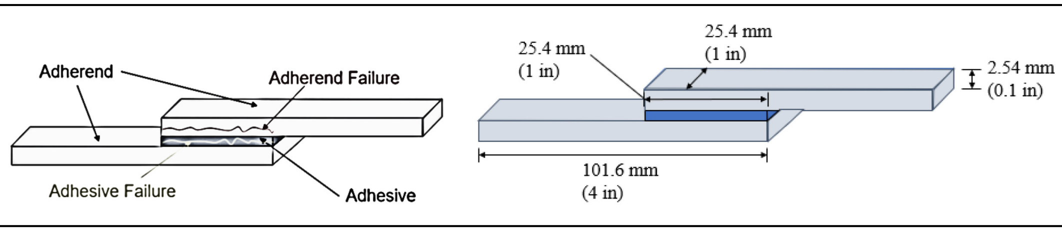

Figure 5: Single lap bond-line of CFRP panels and the ASTM D5868-01 single lap shear strength test's sample configuration [18].

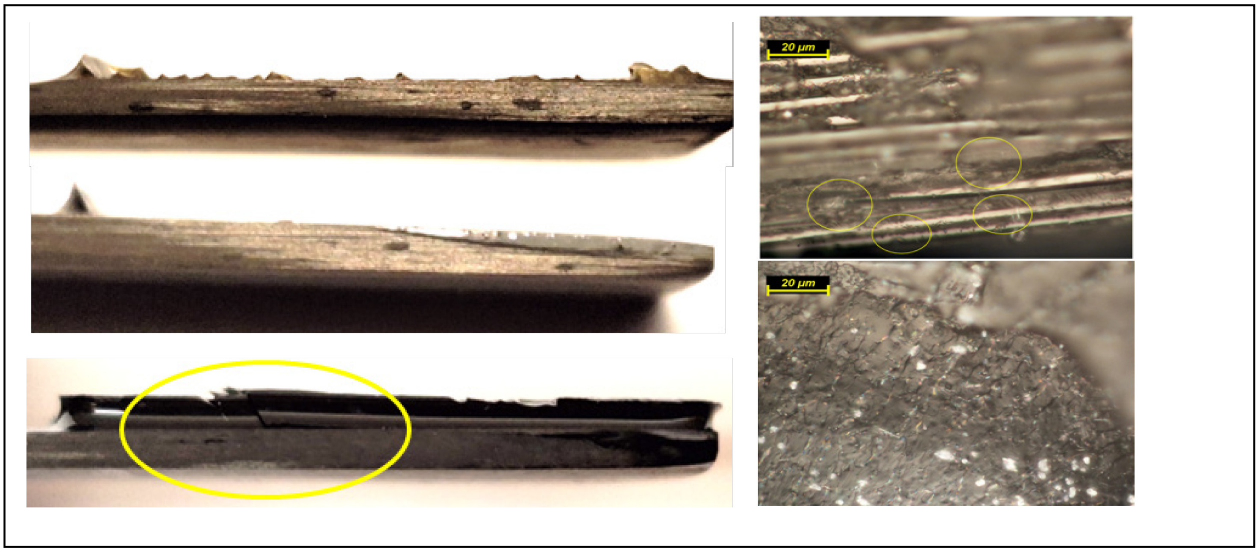

Figure 6: Fracture site profile pictures of the epoxy bonded CFRP (left top), the CNF toughened epoxy adhesive bonded CFRP (left center), and the CNF toughened epoxy adhesive bonded ZT-CFRP (left bottom). The CNF toughened epoxy adhesive helped to move the failure site from the adhesive into the CFRP adherend. The failure site of the CNF toughened epoxy adhesive bonded ZT-CFRP panel presented a further complex failure scenario including delamination along with carbon fiber compressive failure and adhesive film compressive failure along the tensile force direction. Two microscope pictures of the failure sites in ZT-CFRP adherends are also shown (right top and right bottom) [18].

Manufacturing Scalability – Development Towards Roll To Roll Production of Carbon Nanofibers Z-Threaded CFRP (ZT-CFRP) Prepreg

The abovementioned ZT-CFRP prepregs were all manufactured by the labor-intensive batch process as illustrated in Figure 7, as reported in the literature [16]. The unique 1-dimensional flow transfer for the pre-aligned hot-melt CNF/resin film was achieved by vacuum-bag film transfer process under a careful temperature control; any mis-handling could cause the failure of the small batch ZT-CFRP prepreg production. The ZT-CFRP prepreg were invented with roll-to-roll scalable production in mind from the very beginning, but the implementation, design, and construction of the roll-to-roll prepreg machine has not been completed until recently. The author's research group was able to combine the knowledge learned in the past into the design and construction of a successful continuous roll-to-roll hot-melt machine to automate the manufacturing of ZT-CFRP prepreg as illustrated in Figure 8 and explained in [19] along with the ability to adopt different toughened hot-melt epoxy systems for the resin matrix rather than only using neat epoxy (e.g., EPON 862/Epikure-W). Such ability allowed the tuning of the ZT-CFRP prepreg system's curing cycles, prepreg handleability, and performance/cost control by using different resin matrix systems and processing parameters. Due to space limitation, budget, and academic research purpose, the roll-to-roll hot-melt ZT-CFRP prepreg machine was designed to produces ZT-CFRP prepreg up to 254 mm (12 inches) wide and spool out speed of (1 feet per minute).

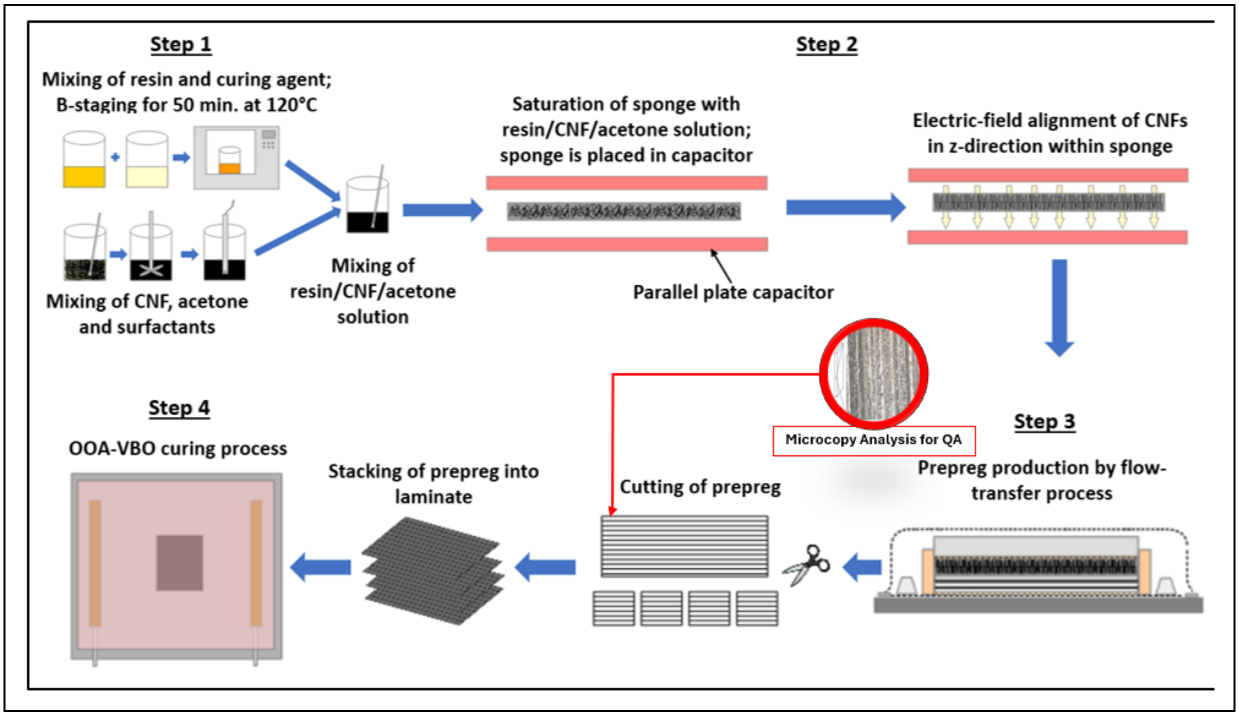

Figure 7: The schematic of the labor-intensive batch-manufacturing process of ZT-CFRP prepreg showed the major steps to manufacture a ZT-CFRP prepreg of small size [16]

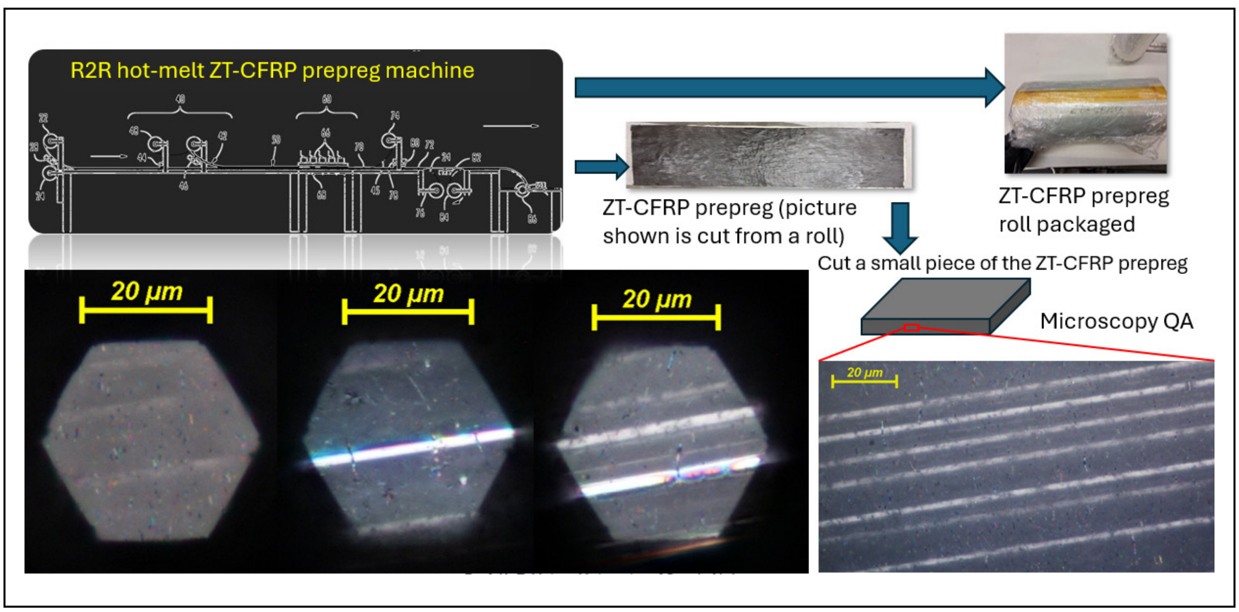

Figure 8: Automated roll-to-roll hot-melt prepreg machine has been used to spool out ZT-CFRP prepreg. The z-threading morphology has been validated with microscopy analysis.

Summary and Future Works

Advanced air mobility (AAM) presents new opportunities for carbon fiber reinforced polymer (CFRP) composites. Different than traditional airliners and automotive industries, AAM aircrafts manufacturers and operators could be benefited from a new CFRP systems tailored to meet their specific needs and concerns including cost, multifunctional performance, manufacturing speed, maintenance, and repair, etc. Nanocomposite advancement such as the nanofibers (or nanotubes) z-threaded CFRP prepreg systems may provide certain interesting properties and multifunctional performances that can be useful to the AAM industry. This paper reviewed the zig-zag CNF z-threaded carbon fiber network microstructure and some reported improvements in mechanical, thermal, and electrical properties. Multifunctionality of the ZT-CFRP also showed the improvements or enabling in non-destructive evaluation (NDE), flame self-extinguishing ability, and adhesive bond-line to joint CFRPs. The manufacturing scale-up to translate the labor-intensive small batch process to an automated roll-to-roll hot-melt prepreg machine to continuously spool out ZT-CFRP prepreg was also discussed in this paper. Table III briefly summarizes the current state of ZT-CFRP prepreg technology discussed in this paper.

Table III: Summary of current state of ZT-CFRP prepreg technology

ZT-CFRP Prepreg or Filament/Tape

- No increase in the CFRP prepreg and laminate thickness. Not an interleafing technology and without the disadvantages of interleafing would introduce!
- Easy to use. Handled and cured like regular CFRP prepregs.
- Affordable/Scalable volume production.

Matrix:

- Hot-Melt Epoxy (other matrices including thermoplastics will also be possible in the future)

Fibers:

- Carbon Fibers (unidirectional, plain weave, etc.) (other fibers will also be possible.)

Nanoparticles:

- CNF
- MWCNT
- Other fillers possible

Applications:

- Sporting Goods, Aerospace, Automotive, Energy, Construction, 3D-Printing, etc.

Experiments showed Improvements:

✓ Interlaminar Shear Strength (ILSS) and possibly Intralaminar Shear Strength
✓ Mode-I delamination toughness
✓ X-directional Compressive Strength (fiber direction)
✓ Z-directional thermal conductivity (thickness direction)
✓ Z-directional electrical conductivity
✓ More consist laminate properties (lower coefficient of variance (C.O.V))
✓ Less susceptible to void-caused property degradation
✓ Allow high carbon fiber volume fraction
✓ Allow highly porous version of ZT-CFRP composites for customized functionalities
✓ Nanostructure-induced flame self-extinguishing and fire-resistance
✓ Improving Adhesive Bond-line Strength
✓ Improving Thermography NDE accuracy and sensitivity
✓ Other properties to be characterized

ZT-CFRP technology enabled an interesting and effective way to process nanofibers/nanotubes into CFRP to create synergetic effects between carbon fibers and nanofibers. Due to the interesting microstructure of ZT-CFRP, many other properties and multifunctionality may be worthy of investigation in the future; for example, in-plane shear strength, sound propagation/damping behavior, extreme temperature properties (after using high-temperature matrix system), response to alternative electrical waves, etc. It is hopeful that nanocomposites technologies such as the ZT-CFRP composites can provide attributes that are useful to the AAM industry in the future.

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