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Evaluating the Lightning Strike Damage Tolerance for CFRP Composite Laminates Containing Conductive Nanofillers

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Abstract

Conductive nanofillers, such as carbon nanotube, graphene nanoplatelets, and carbon black particles (with diameters in nanometers) have been shown to enhance the electrical conductivity of fiber reinforced polymer matrix composites in many existing studies. The motivation is primarily for lightning strike protection, electromagnetic interference shielding, de-icing, and the manufacturing of lightweight electronic components. In this paper, we evaluate the lightning strike damage tolerance of carbon fiber reinforced polymer (CFRP) matrix composite laminates containing conductive nanofillers with varying weight fractions, including carbon black (CB), carbon nanotubes (CNT), and a mix of CB and CNT, through simulated lightning strike tests, followed by both non-destructive ultrasonic inspection and destructive sectioning to characterize the damage inflicted by the simulated lightning strike. Three-point flexural tests are performed to evaluate the residual strength retained by all CFRP specimens. Results show that lightning strike damage experienced varying levels of reduction for CFRP composite specimens containing conductive fillers in comparison to the baseline specimen without fillers. Notably, the delamination only penetrated to the interface between the 1st and 2nd layer for the specimen with 0.25 wt.% CNT in comparison to the baseline CFRP specimen for which the delamination penetrated to the interface between the 5th and 6th layer. Moreover, the retention of the flexural modulus increased from 26.5% to a maximum of 95.0% for the specimen with 0.25 wt.% hybrid CB and CNT. Yet, we show that using our chosen conductive fillers cannot fully eliminate lightning strike damage. Additionally, adding conductive fillers could compromise the flexural properties. We provide discussions on future recommendations on using conductive fillers for the lightning strike protection of CFRP composites.

Keywords Lightning strike · Conductive fillers · Carbon fiber reinforced polymer (CFRP) matrix composites · Lightning damage mitigation · Strength retention after lightning strike

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1 Introduction

Using conductive nanofillers, such as carbon nanotube, carbon black, and graphene nanoplatelets, to improve the electrical conductivity of carbon fiber reinforced polymer (CFRP) matrix composite materials is a well-studied topic by many research groups around the world [1–4]. The motivation of such studies is primarily driven by the pressing needs for novel lightweight solutions of lightning strike protection [5–7], electromagnetic interference shielding [8], de-icing [9], as well as the manufacturing of lightweight electronic components [10]. Many studies have shown increase in the electrical conductivity of CFRP composites with added carbon nanotubes [11–15]. For instance, Dong et al. reported a 588% improvement of out-of-plane electrical conductivity with 2.5 wt% of added CNTs from 1.16 to 7.78 S/m [11], in comparison with their neat CFRP composite. Bekyarova et al. reported an improvement of out-of-plane electrical conductivity from 6.8 to 8.9 S/m [12]. Pu et al. reported an electrical conductivity improvement of their silver-filled electrically conductive adhesive from 1×10^{-7} to 714 S/m by adding 5 wt% of the nitrogen-doped graphene nanosheets [13]. Although many studies have proved the enhancements in the electrical conductivity of CFRP composites by adding conductive nanofillers [16–19], it is still unclear how CFRP composites containing these conductive nanofillers behave under lightning strike. The effectiveness of the improved electrical conductivity of CFRP composites against lightning strike events remains to be investigated. In other words, what is the readiness of this technology for practical applications? To answer this question and provide future directions in using conductive fillers for lightning strike protection of various CFRP composite structures [20, 21], including adhesively bonded sandwiched composites [22], in this study, we focus on experimentally evaluating the lightning strike damage tolerance of CFRP composites containing conductive nanofillers with varying weight fractions. The primary objective of the current work is to evaluate the lightning strike damage tolerance of CFRP composites containing conductive nanofillers including carbon black (CB), carbon nanotubes (CNT), and a mix of CB and CNT at varying weight fractions, and to infer, through the results of the simulated lightning strike tests, the feasibility of replacing traditional methods of lightning strike protection with lightning strike protection through direct modifying of the resin matrix by adding conductive nanofillers.

Note that traditional methods of lightning strike protection for CFRP composites typically rely on using a layer of expanded metal mesh or film on top of the CFRP structures to create a path of low electrical resistance for the incoming lightning current. However, using the metal mesh will add weight to the structures and significantly compromise the weight saving benefits of using CFRP composites. Furthermore, this method requires more complicated treatments, for instance: (i) a thin, corrosion resistant layer of fiberglass often needs to be inserted in between the metal mesh and the CFRP composite layer to prevent the galvanic corrosion and (ii) adhesive needs to be used to adhere the fiberglass layer to the CFRP layer and adhere the metal mesh to the fiberglass layer [9]. Moreover, the durability of the adhesion will be challenged by the thermal mismatch and the environmental degradations during practical operations.

The above-mentioned complications, along with the durability issues and the significantly added weight, inevitably lead to higher manufacturing and maintenance costs, which in turn drive the research into developing more convenient and efficient methods of lightning strike protection for composite structures. One of such methods is to use conductive fillers to improve the electrical conductivity of CFRP composites, which is advantageous especially because the existing product manufacturing lines for conventional CFRP composites could simply replace the current insulating resin with the conductive resin for manufacturing CFRP composites with higher electrical conductivity, without having to modify the existing production line. A thorough review of conductive fiber reinforced polymer matrix composites for lightning strike protection is presented in Ref. [23].

In the current work, we performed standard simulated lightning strike tests with CFRP composite specimens containing conductive nanofillers of carbon black (CB), carbon nanotube (CNT), and a mix of CB and CNT, with varying levels of weight fractions. The choice of these nanofillers is due to their high electrical conductivity [24] and the reported improvement in the electrical conductivity of CFRP composites when mixing these nanofillers into the CFRP composites [9]. These tests were followed by post damage material characterization, as well as mechanical residual strength tests to investigate the effects of weight contents of conductive nanofillers on the lightning strike damage mitigation for CFRP composites. The results will be followed by our discussions and future recommendations for using conductive nanofillers for the practical lightning strike protection of CFRP composites.

2 Experimental Systems

2.1 Materials and Specimens

The materials we used for the standard lightning strike tests are CFRP composites manufactured with 3 K 2×2 twill weave carbon fiber fabrics from Fibre Glast Developments Corp., which has a tensile strength of 4.38 GPa and tensile modulus of 241 GPa, and Adtech 820/824 epoxy resin from Soller Composites Corp. for the matrix. Similar 2×2 twill weave carbon fiber fabrics have also been used in works of Muñoz et al. [25] and Katunin et al. [26]. Moreover, same materials and layup orientation have been used in our previous series of studies on impact of lightning channel diameter and ground electrode edge insulation on damage tolerance of CFRP composites during simulated lightning strike tests [27, 28]. The conductive nanofillers used in this study include COOH functionalized multiwalled carbon nanotubes (diameter 20 nm, length 1–15 µm, and electrical conductivity > 1e4 S/m) and carbon black nanoparticles (diameter 200–300 nm and electrical conductivity > 333 S/m). Functionalized multiwalled carbon nanotubes (MWNTs) were chosen over raw MWNTs as they have been reported to provide better dispersion efficacy [29, 30]. Also, note that multiwalled CNTs were used instead of single walled CNTs (SWNTs) in this study since MWNTs have been proved to perform better in improving electrical conductivity than SWNTs, as reported in Refs. [12, 31, 32].

The specimens were fabricated using the conventional wet layup procedure. Before laying up, conductive fillers with varying weight fractions were dispersed into the epoxy resin using the same procedure as reported in Ref. [33]. The procedure has been proved to provide a uniform dispersion. For example, Fig. 1 is a microscopic image of the fracture surface of a CFRP composite specimen that we obtained using scanning electron microscopy (SEM), in which we can clearly observe the uniform dispersion of CNTs in the epoxy resin. Note that the carbon fiber filament channel is created upon detaching of carbon fiber filament from resin matrix when creating the fracture surface for SEM imaging. The layup orientation is $[0/90/0/90]_s$ with regard to the warp direction of the woven fabric, to be consistent with our previous work on investigating the impact of lightning channel diameter

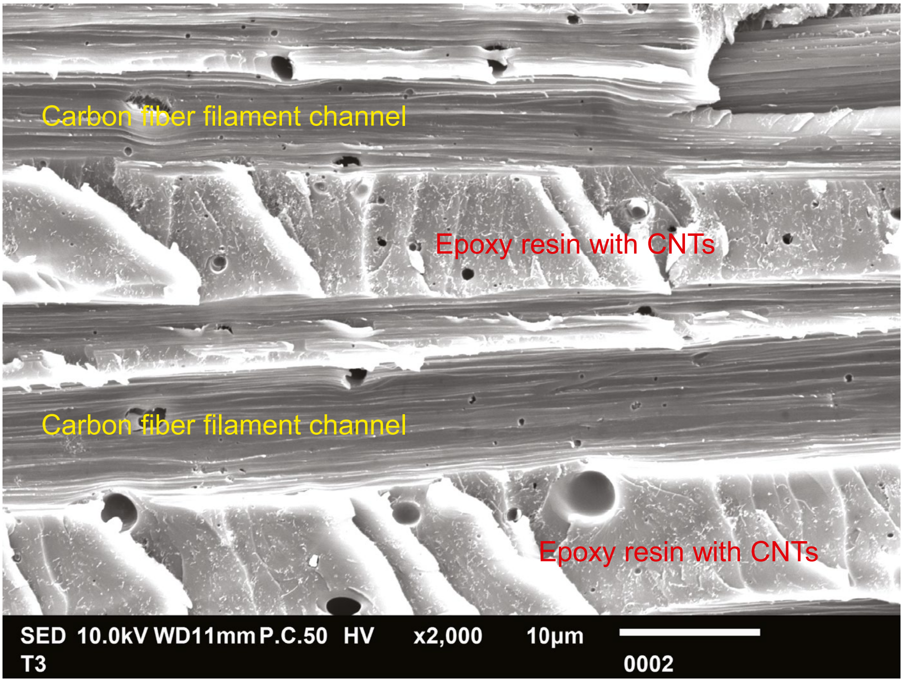

Fig. 1 SEM image of the fracture surface of the CFRP composite specimen containing CNTs

on the damage of CFRP composites [27, 28]. After curing, the prepared laminates were trimmed to a size of 230 mm × 230 mm.

Table 1 lists the information of the CFRP composites that we prepared, including the specimen labels, the weight fraction of the specific conductive nanofillers added to each

Table 1 The CFRP composite specimens used for simulated lightning strike tests

Specimen	Specimen information		Lightning strike impulse tests
R2	Reference (baseline) CFRP		100 kA
B1	CFRP with CB nanofiller	0.25 wt.% CB	
B2		0.50 wt.% CB	
B3		0.75 wt.% CB	
T1	CFRP with CNT nanofiller	0.25 wt.% CNT	
T2		0.50 wt% CNT	
T3		0.75 wt.% CNT	
C1	CFRP with CB + CNT nanofillers	0.125 wt.% CB + 0.125 wt.% CNT	
C2		0.25 wt.% CB + 0.25 wt.% CNT	
C3		0.375 wt.% CB + 0.375 wt.% CNT	

specimen, and the lightning strike current imposed to each specimen. Note that only one specimen is tested for each condition due to the high cost of material supplies and the experimental testing. More experimental replications will be conducted in our future studies to understand the statistical variations. Nevertheless, it is not uncommon to use only a single testing specimen considering the manufacturing costs and time. Many studies on simulated lightning strike tests of CFRP composites tested only one specimen per testing conditions due to the high material costs and the time to prepare and manufacture specimens [34–38]. Also note that for the current work, we attempted to increase the weight fraction of either the CB or the CNT fillers to 1.00 wt.%, when mixing them with the epoxy resin. However, the mixture became overly viscous and cannot be used for the manufacturing of CFRP composite specimens. This is consistent with the finding reported in Ref. [16]. Three levels of weight fractions of nanofillers were used to mix with the epoxy resin and fabricate the conductive CFRP composites. They are 0.25 wt.%, 0.5 wt.%, and 0.75 wt.%. The same three levels of weight fractions are used in Ref. [19]. The effect of the weight fractions of nanofillers on the resulting electrical conductivity of CFRP composites is well studied in many existing studies [2, 9, 10, 19, 39], and thus, is not investigated in this paper.

2.2 Waveform A Simulated Lightning Strike Tests

The fabricated specimens were subjected to simulated lightning strike tests at the High Voltage Lab of Mississippi State University (MSU-HVL). The impulse current waveform generated at MSU-HVL conforms to the lightning waveform A current suggested by the lightning strike testing standard, i.e., SAE-ARP5416 [40]. For the current tests, an impulse current discharge of 100 kA was generated and used for the lightning strike damage tests. Note that the 100 kA impulse current represents a typical lightning strike measured in nature (*i.e.,* between 50 and 1% of the measured values [41]).

To perform the simulated lightning strike tests, all testing specimens were attached to a grounding fixture, which is made of a copper plate with a cutout window of 130 mm × 130 mm. Braided copper wires were placed between all four edges of specimens and the copper plate (see Fig. 2). To avoid electrical arc discharge jumping from the electrode to the edge of the grounding fixture, insulation tapes were applied around the four edges of the cutout window of the copper plate [27]. The grounding fixture and the high

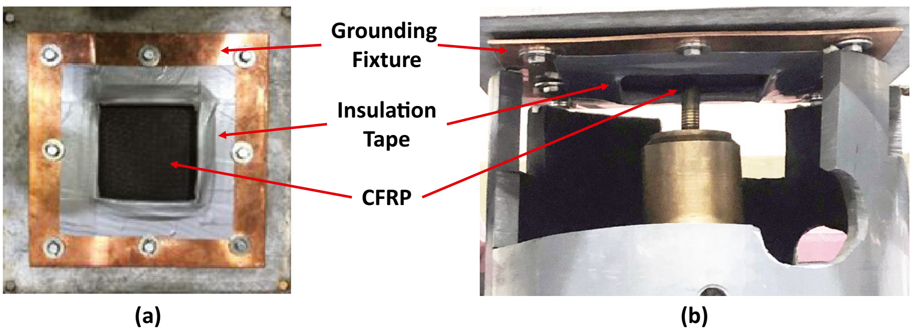

Fig. 2 Photos of the (**a**) grounding fixture and (**b**) the high current impulse generator for the simulated lightning strike tests

current impulse generator for the simulated lightning strike tests are shown in Fig. 2. The diameter of the copper electrode (in a cylindrical shape with a hemisphere head) is 46 mm. The arc gap between the electrode and the surface of the CFRP composite specimen is 3 mm.

Note that the size of the electrode and the arc gap distance can have considerable impacts on the lightning strike damage in CFRP composites. The effects of the electrode size and the arc gap distance on the characteristics of the electric arc plasma and the resulting damage in CFRP composite materials are discussed in our previous work in Ref. [27]. In this study, for consistency, the testing parameters (i.e., electrode size and arc gap distance) were kept constants throughout our lightning strike tests for all specimens.

2.3 Post-damage Material Characterization

Following the simulated lightning strike tests, ultrasonic inspections were conducted using the OmniScan SX ultrasonic flaw detector equipped with a 64 element, 5 MHz phased array probe. The inspections allowed us to inspect the extent of the interlaminar delamination (i.e., depth and area) caused by the lightning strike impact. After the non-destructive ultrasonic inspection, three-point flexural tests were conducted according to the ASTM D7264 standard [42] to examine the degradation of flexural modulus and strength after the lightning strike impact. Figure 3 shows a schematic of the three-point flexural test. The overall length of the specimen was 76 mm long and 13 mm wide. The length of the support span was 64 mm and the speed of testing was 1 mm/min, as suggested by the standard [42]. Prior to the three-point flexural tests, cross-sectional microscopy images were taken for all coupon samples with a Hirox KH-8700 digital microscope to inspect the detailed damage modes across the thickness of the composite caused by the lightning strike impact.

3 Results and Discussion

3.1 Damage Characterizations After Lightning Strike Tests

After performing simulated lightning strike tests, the lighting strike damage of specimens were evaluated through visual observation and ultrasonic inspection, followed by the cross-sectional microscopy. The left side of Fig. 4 shows the visible damage for all testing specimens taken by a camera. It can be clearly seen that the reference (baseline) CFRP specimen underwent the most severe damage where multiple damage modes can be observed, including fiber breakage, fiber pullout, matrix cracking, surface material removal, charring, and delamination. Here, note that through our series of simulated lightning strike tests performed in our previous studies [27, 28], we have made improvements to our testing rigs to produce consistent simulated lightning strike test results. Specifically, consistent lightning

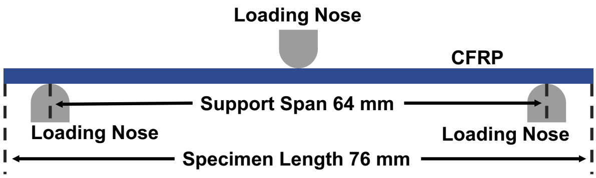

Fig. 3 Schematic of the three-point flexural test fixture

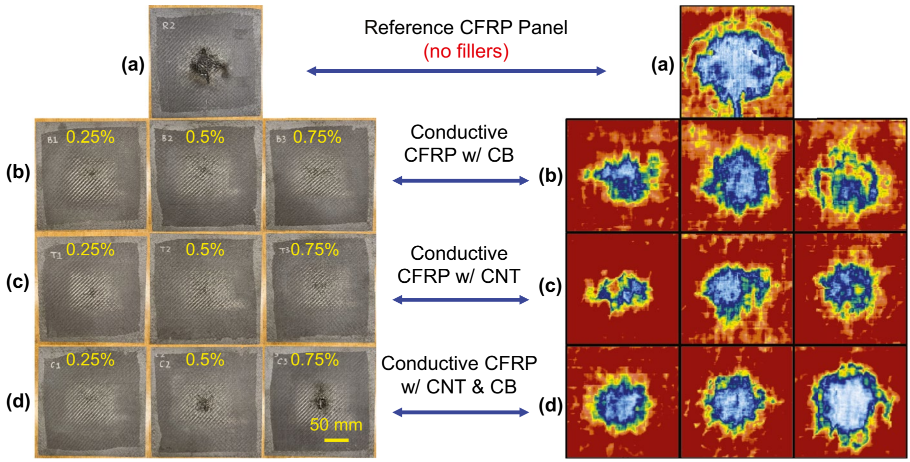

Fig. 4 Visual inspection photos and ultrasonic c-scan images for (from top to bottom): (**a**) reference (baseline) CFRP, (**b**) CFRP with carbon black (CB) nanofiller, (**c**) CFRP with carbon nanotube (CNT) nanofiller, (**d**) CFRP with a mix of CB and CNT nanofillers

attachment points are ensured by the improved grounding insulation provided by insulation tapes around the copper fixture to ensure the lightning arc striking the CFRP specimen surface instead of going through the path of the grounding fixture edge directly. Given the consistent simulated lightning strike waveform and lightning arc attachment points, the locations of the delamination would be expanding outwards from the lightning arc attachment point as is evident in the ultrasonic c-scan image of Fig. 4, where all the detected delamination form a circular shape and they are all near the center of the tested specimens.

The lightning strike damage mechanisms of CFRP composites are widely studied in the literature [43–49]. To briefly mention, the extremely high lightning current resulted in a rapid temperature rise in the composite specimens (up to 3316 °C) and lead to the decomposition of epoxy resin. The epoxy resin typically starts to decompose at 300 °C and is fully decomposed at 500–800 °C. The surface mass loss is caused by the vaporization of epoxy resin and the sublimation of the carbon fiber. The fiber breakage, fiber pullout, and matrix cracking are potentially caused by the interlaminar pressure from the accumulated pyrolysis gases that are trapped between layers. The delamination is potentially caused by two main mechanisms: (i) the decomposition of epoxy resin between adjacent layers and (ii) the out-of-plane pressure load from the acoustic shock wave produced during the lightning strike impact [50].

As we can see from visual observation photos, for all CFRP composite specimens containing conductive nanofillers, the lightning strike damage is much smaller in comparison to the baseline CFRP specimen. In terms of the observable surface material removal, specimens with only one type of added conductive nanofiller, namely, CB or CNT, exhibited no significant difference. While for the specimens with a mix of both CB and CNT nanofillers, more severe fiber pullouts and fiber breakage can be observed with the increase of the weight fraction of the total added nanofillers.

It is worth noting that existing experimental results and numerical simulations showed that the use of the hybrid fillers of CB and CNT can provide positive synergistic effects for improving the conductivity of some polymers [3, 51]. However, this is only true when the weight fraction of the CB or the CNT is close to the electrical percolation threshold. In our specimens, the weight fractions of CNT and CB are still below their percolation thresholds [52, 53], and thus, the synergistic effects from CB and CNT are not active. Furthermore, as one can notice from Fig. 4(d), the damage area increases as the total weight fraction of the nanofillers increases for the specimen. This implies that when the synergistic effect of the CB and CNT is not active, adding more CB fillers could be detrimental to the lightning strike protection of CFRP composites.

The right side of Fig. 4 shows the corresponding C-scan images for all the testing specimen presented in the same order as the visual observation photos on the left side. Note that the ultrasonic B-scan would provide additional information on the locations of delamination in terms of depth along a single line of interest. However, in the current work, knowing that flexural tests would be performed which required cutting out strips of 76 mm × 13 mm from the CFRP specimens at six different locations, we performed optical microscopy on the cross section of the strips from center of the damage to observe the locations of delamination in thickness direction instead of conducting the ultrasonic B-scan. Figure 5 shows the delamination area obtained using the ImageJ software, where the top red line represents the delamination area of the baseline CFRP specimen. It can be seen that the baseline CFRP specimen showed the largest delamination area of approximately 3589.69 mm^2 and that the CFRP laminate containing 0.75 wt.% of hybrid CB and CNT showed a delamination area nearly the same as the baseline specimen. A generally increasing trend in the delamination area can be observed with the increase of weight fraction of added conductive nanofillers, with an exception for the case with 0.5 wt.% of CNT, which showed

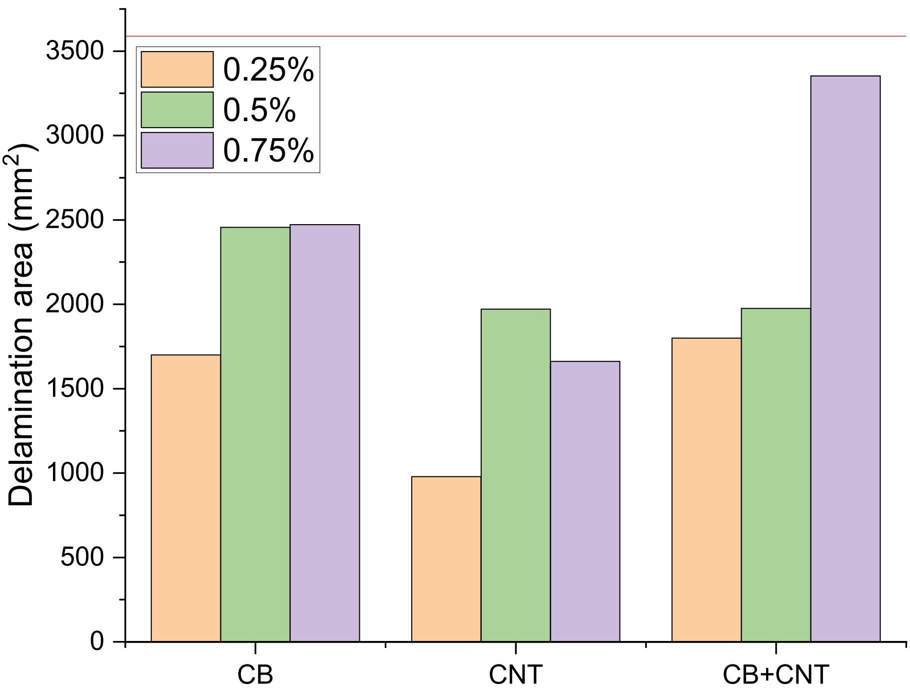

Fig. 5 Delamination area for all specimens obtained using ImageJ. (*Note:* the top red line represents the delamination area of the baseline CFRP composite specimen)

a larger delamination area than that of the 0.75 wt.% of CNT. It is worth mentioning that increasing in weight fraction of nanofillers at lower percentage would increase the fracture toughness, but up to a certain point (depending on the resin matrix used), adding additional nanofillers would start to have adverse effects as evident in the works of Chaudhry et al. [54] where mode I fracture toughness was measured with increasing areal density of CNT loading, and it was found that the mode I fracture toughness was highest at 1 g/m^2 CNT loading and started to decline with further addition of CNTs. Faulkner et al. [55] found that adding 5 g/m^2 CNT loading resulted in even lower mode II fracture toughness than the pristine specimen. Takeda and Narita [56] found that adding MWNTs at 0.32 wt% provided the highest mode I fracture toughness then started to decline with MWNTs loading beyond 0.32 wt%, with the case of 1.3 wt% MWNTs resulted in even lower mode I fracture toughness than the pristine specimen.

Figure 6 shows the microscopy images for all our tested specimens taken across the thickness of the specimens in the center of the lightning damaged sites. The damage modes in the CFRP composites caused by the lightning strike impact, including the fiber breakage and pullout, surface resin vaporization, and delamination can be clearly observed.

It should be noted that although it appears that specimens C2 and C3 exhibited more significant fiber breakage and fiber pullout than the baseline CFRP specimen (i.e., specimen R2) from the microscopy images (see Fig. 6), it is only due to the large delamination area of specimen R2 which exceeds the 76 mm × 13 mm area cut out for observation, the delaminated plies had no attachment on the cut out area, rendering the complete removal of plies 1 and 2 of specimen R2. The visual observation photos in Fig. 4 showed an overall picture of the extent of the fiber breakage and fiber pullout on the surface of each specimen, in which we can see that the fiber breakage and fiber pullout are much

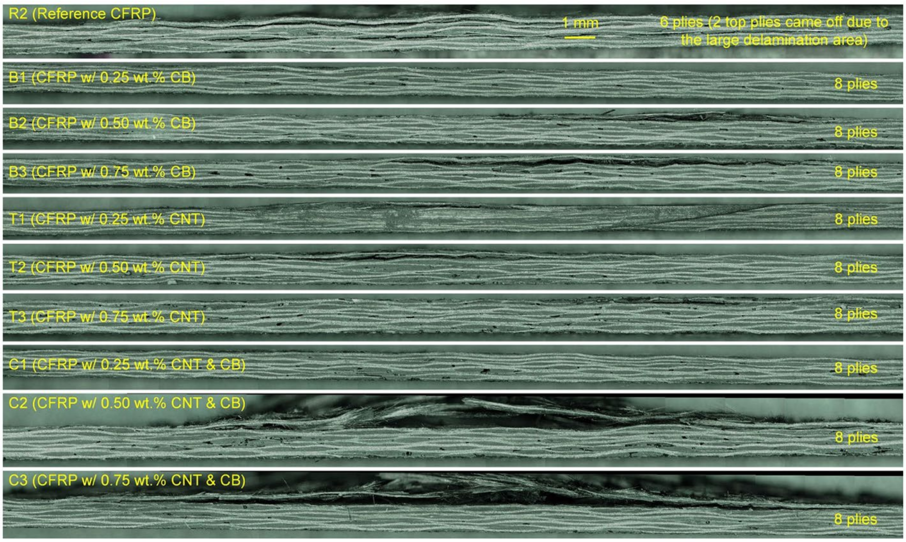

Fig. 6 Microscopy images for the reference (baseline) CFRP composite specimen and CFRP composite specimens with conductive nanofillers (see Table 1 for the labeling of specimens) after lightning strike tests. *Note:* the delamination area of specimen R2 exceeded the 76 mm × 13 mm area cut out for microscopy observation and the top two plies were completely removed

more significant in the reference CFRP specimen than any other specimens with conductive nanofillers, including specimens C2 and C3.

As one can see from Fig. 6, the baseline CFRP specimen suffered the most severe delamination damage and the delamination penetrated to the interface between the 5th and the 6th ply. In contrast, the delamination in specimens with conductive nanofillers reduced to the interface between the 2nd and 3rd ply. For specimen C1 (i.e., the one with 0.25 wt.% CNT & CB), the delamination further reduced to the 1st and 2nd ply only.

Table 2 lists the delamination penetration depth and the delamination area for all specimens. As one can see, although the difference in the delamination penetration depth for CFRP specimens containing varying weight fractions of conductive nanofillers is insignificant, the extent of the delamination area generally increases with increasing weight fraction of conductive nanofiller. The increasing extent of the delamination area may suggest that increasing the weight fraction of conductive nanofiller potentially increases the area of the electric arc attachment on the surface of the CFRP. Further investigation is needed to understand this mechanism through simulations.

3.2 Flexural Properties

The flexural strength, σ, and the flexural strain, ε, are calculated according to the ASTM D7264 standard [42],

$$\sigma = \frac{3PL}{2bh^2} \tag{1}$$

$$\varepsilon = \frac{6\delta h}{L^2} \tag{2}$$

where P is the applied force, L is the support span, b is the width of the specimen, h is the thickness of the specimen, and δ is the mid-span deflection.

Table 2 The delamination area and the delamination penetration depth for the baseline and conductive CFRP composite specimens

Specimens		Delamination area (mm)	Delamination penetration depth
Reference (baseline) CFRP		3589.69	5th/6th ply
CFRP with CB	0.25 wt.% CB	1700.52	2nd/3rd ply
	0.50 wt.% CB	2455.65	2nd/3rd ply
	0.75 wt.% CB	2472.06	2nd/3rd ply
CFRP with CNT	0.25 wt.% CNT	978.76	2nd/3rd ply
	0.50 wt.% CNT	1971.25	2nd/3rd ply
	0.75 wt.% CNT	1661.50	2nd/3rd ply
CFRP with CNT + CB	0.125 wt.% CNT + 0.125 wt.% CB	1800.09	1st/2nd ply
	0.25 wt.% CNT + 0. 25 wt.% CB	1975.56	2nd/3rd ply
	0.375 wt.% CNT + 0.375 wt.% CB	3353.41	2nd/3rd ply

The flexural modulus, E_f, is calculated by,

$$E_f = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{3}$$

where $\Delta\sigma$ is the difference in flexural stress between two selected strain points and $\Delta\varepsilon$ is the difference between two selected strain points.

Figure 7(a) and (b) show the flexural modulus and the flexural strength, respectively, obtained for undamaged samples. These data are for "undamaged samples" because the testing coupons for the three-point flexural tests were extracted from the edges of each specimen, which are far away from the lightning damaged site. The data are plotted with errors bars to account for the statistical variability. The red horizontal line in these figures represents the calculated flexural modulus and strength for the baseline specimen. The flexural modulus and strength for undamaged specimens are used to understand how the added nanofillers affect the mechanical properties of CFRP composites before lightning strike. Note that the calculated flexural strength and flexural modulus values are in the same order of magnitude to those reported in existing studies [57, 58]. For instance, Azimpour-Shishevan et al. reported flexural strength of 489.6 MPa and flexural modulus of 53.7 GPa [57], Srivastava et al. reported flexural strength of 629 MPa and flexural modulus of 44 GPa [58], both using 3 K twill weave carbon fiber fabrics. The obtained flexural strength of our CFRP specimens of 642.14 MPa and flexural modulus of 45.38 GPa are in fair agreement with data presented in related studies. The slight variations inevitably exist as the fabrics are from different manufacturers.

It can be seen, specimens containing conductive nanofillers showed varying levels of reductions in both the flexural modulus and strength, in comparison to those of the baseline specimen, except for the specimen with 0.25% CNT, for which the flexural modulus is comparable to the baseline specimen while the flexural strength is even higher than the baseline specimen. For the flexural modulus, the maximum reduction is about 11%, found for the specimen with 0.75% CB. For the flexural strength, the maximum reduction is about 15%, found for the specimen with 0.75% CNT. These reductions raise concerns over using conductive nanofillers for practical lightning strike protection in the future. Specifically, although conductive nanofillers significantly decreases the lightning strike damage, as

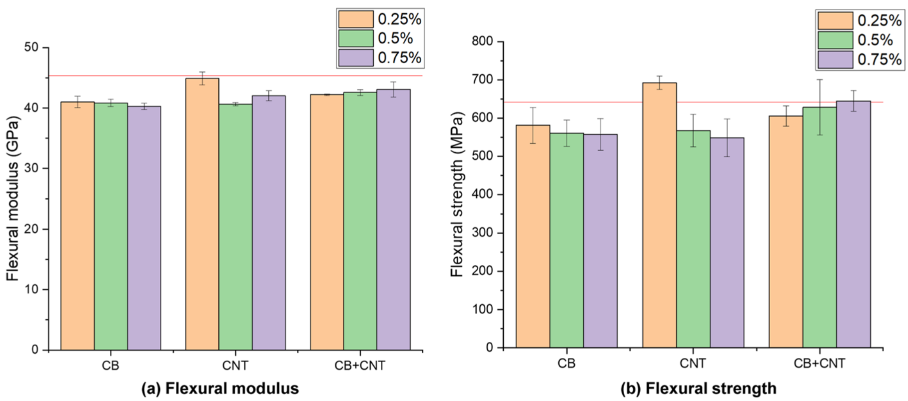

Fig. 7 Flexural properties: (**a**) modulus and (**b**) strength for samples taken at the edge of each specimen (undamaged specimens). *Note:* the top red line denotes results of the reference specimen

shown in Fig. 4, adding them potentially sacrifices the flexural modulus and strength of the CFRP composites. Similar trends have also been reported by Vahedi et al. [59] where flexural modulus increased as the weight fraction of added CNT increases from 0 to 0.25 wt%, peaked at 0.25 wt% and then started to decline beyond 0.25 wt%. Hossain et al. [60] reported flexural modulus peaked at 0.3 wt%.

Table 3 lists the flexural modulus and strength for both damaged and undamaged coupon specimens and the percentage retentions after the lightning strike. Here, the lightning strike damage tolerance of the composite specimens is evaluated by checking the retentions of the flexural modulus and strength after the lightning strike. As one can see, the baseline specimen exhibited both the lowest modulus retention (26.5%) and lowest strength retention (28.0%), as expected. The specimens containing conductive nanofillers generally showed significantly higher modulus and strength retentions than the baseline specimen, with the minimum modulus and strength retentions being 59.8% and 54.1%, respectively, found for the case with a mix of 0.25 wt.% CNT and 0.25 wt.% CB nanofillers. The maximum modulus retention is 95.0% for the case with a mix of 0.125 wt.% CNT and 0.125 wt.% CB nanofillers, while the maximum strength retention is 87.3% for the case with 0.75 wt.% CNT.

It can be noticed that for specimens with CB nanofillers, the retentions of flexural modulus and strength did not show a clear trend with respect to the increase of weight fractions. It appears that adding more CB nanofillers does not necessarily improve the modulus or strength retentions. In fact, the modulus retention dropped from 93.1% to 79.7% and the strength retention reduced from 85.0% to 83.8% when the weight fraction of CB nanofillers increased from 0.25 wt.% to 0.75 wt.%.

For specimens with CNT fillers, increasing the weight fraction appears to be beneficial for improving the modulus and strength retentions in general. However, such an improvement (i.e., the increase of modulus and strength retentions) is not linear. As one can see, the modulus retention first drops from 74.9% to 71.9% and then jumps up to 91.2% when the weight fraction increases from 0.25% to 0.50% and then to 0.75%, respectively. The same trend can also be found for strength retentions.

For specimens with a mix of CNT and CB fillers, the modulus and strength retentions are generally much lower than those of the specimens with only one added nanofiller. This effect is more pronounced when the weight fraction increases. This finding agrees with the damage shown in the damage photos and ultrasonic inspection images (see Fig. 4). It also agrees with the delamination area presented in Fig. 6, where the case with a mix of 0.375 wt.% CNT and 0.375 wt.% CB showed the largest delamination area. It should be mentioned that the modulus and strength retentions are not only dependent on the delamination areas, but also dependent on other factors, such as the delamination depth, the amount of surface material loss, and the amount of fiber breakage, fiber pullout, and matrix cracking.

4 Discussions and Future Recommendations

Our experimental investigations show that conductive nanofillers significantly reduced the lightning strike damage in CFRP composite specimens when compared to the baseline composite specimen. This is due to the improvement in the electrical conductivity, which has been experimentally proved in many existing studies (see Ref. [9] for example and references therein). Despite the significant reductions, it is challenging to completely eliminate the lightning strike damage in CFRP composites by only using

Table 3 Retentions of flexural modulus and strength for samples after the lightning strike (100 kA impulse current)

		Flexural modulus (GPa)			Flexural strength (MPa)		
		undamaged	damaged	retention	undamaged	damaged	retention
Reference CFRP		45.38	12.02	26.5%	642.14	179.56	28.0%
CFRP with CB	0.25 wt.% CB	41.02	38.21	93.1%	580.93	493.72	85.0%
	0.50 wt.% CB	40.87	31.45	76.9%	560.33	448.27	80.0%
	0.75 wt.% CB	40.28	32.10	79.7%	557.20	466.90	83.8%
CFRP with CNT	0.25 wt.% CNT	44.90	33.65	74.9%	692.06	531.35	76.8%
	0.50 wt.% CNT	40.65	29.24	71.9%	567.55	362.88	63.9%
	0.75 wt.% CNT	42.03	38.34	91.2%	548.28	478.73	87.3%
CFRP with CNT + CB	0.125 wt.% CNT + 0.125 wt.% CB	42.22	40.11	95.0%	605.26	506.85	83.7%
	0. 25 wt.% CNT + 0. 25 wt.% CB	42.58	25.47	59.8%	628.36	339.88	54.1%
	0.375 wt.% CNT + 0.375 wt.% CB	43.09	25.94	60.2%	644.51	404.42	62.7%

conductive nanofillers as the improvement in the electrical conductivity of the CFRP composites by using the nanofillers is still insufficient. Although electrical characterization tests were not conducted for specimens used for this study due to the limited scope of this project, experimental testing data are widely available in the literature. For example, it was reported that the addition of 0.4 wt.% double walled CNTs increased the through-thickness electrical conductivity by only one order of magnitude, from 0.015 to 0.108 S/m, whereas in the other two directions the conductivity is not much affected [18]. The same finding was also reported by Ref. [16]. Furthermore, it was reported that the through-thickness electrical conductivity of the CFRP composites increased from 0.216 to 0.250 S/m when the loading of CNT increased from 0.25 to 0.5 wt.%, but when further increasing the loading to 0.75 wt.%, the electrical conductivity dropped to 0.226 S/m [19]. These experimental data show that the improvement in the electrical conductivity of the CFRP composites is still far from sufficient, especially considering that the traditional lightning strike protection system using copper mesh has an electrical conductivity in the order of 10^7 S/m.

One would naturally suggest keeping increasing the weight fraction of the conductive nanofillers in order to achieve higher electrical conductivity. However, the dilemma is that when increasing the weight fraction of the nanofillers, many other properties of the epoxy resin mixture will be simultaneously changed. This includes the increase of the viscosity, the change in the rheological properties, such as the storage and loss modulus, and the increase of the gel time [16]. A high viscosity will make the epoxy resin mixture unsuitable for the manufacturing of the CFRP composites, especially when using the resin infusion process. Additionally, it has been pointed out that the changes in the rheology of the epoxy system and the reduction of the gel time led to the formation of defects such as voids, bubbles, and other structural discontinuities, which can adversely affect the thermal and electrical conductivities [16]. It has also been experimentally proved that the addition of small amount of carbon nanotubes to epoxy resin improves flexural strength, but only for lower amount of CNTs. When the CNTs weight fraction increases over 0.5 wt.%, the bending strength decreases due to defects formation [16]. This trend also agrees with what we found in this study, as shown in Fig. 7.

When compared to the traditional copper mesh solution, the solution of using conductive nanofillers is still not mature yet. Existing experimental studies have demonstrated the effectiveness of using expanded copper mesh for lightning strike protection of CFRP composites [61]. Although lightning strike causes the local vaporization of the expanded foil grids, the underlying CFRP composite remains intact [61]. Moreover, when using the conductive nanofillers for lightning strike protection, the trade-off between the performance and the cost remains a big barrier that hinders this technology from being brought to practical applications. This is due to the high cost of materials, especially for carbon nanotubes, and the limitation of the performance enhancement in the lightning strike protection (i.e., still cannot fully eliminate the lightning strike damage).

Future research is recommended to investigate methods to further increase the weight fractions of nanofillers in the CFRP composites while, at the same time, conduct modeling studies to understanding the effect of weight fractions of nanofillers on the overall anisotropic electrical conductivity. Currently, the weight fraction of nanofillers is limited due to the concurrent change in the rheological properties after mixing them with the epoxy resin and potential agglomeration issues. Additionally, models need to be developed to help us identify the optimum weight fractions of nanofillers in the direction of minimizing the lightning strike damage. Finally, future research is also recommended to investigate the effects of nanofillers on microstructure and the mechanical properties, such as the porosity, defects, translaminar fracture toughness, delamination resistance, to ensure that adding nanofillers does not compromise mechanical properties.

5 Conclusion

In this work, we evaluated the lightning strike damage tolerance of CFRP composites containing conductive nanofillers of carbon black (CB), carbon nanotubes (CNT), and a mix of CB and CNT at varying weight fractions. Our experimental investigations showed that.

- The delamination area and depth experienced significant reductions in specimens containing nanofillers, in comparison to the baseline specimen (with no nanofillers).
- The maximum reduction in the delamination penetration depth was found for the specimen with 0.25 wt.% CNT in which the delamination only penetrated to the interface of 1st/2nd ply, whereas delamination penetration to the interface of 5th/6th ply was observed for the baseline specimen.
- Specimens with added nanofillers showed significantly higher residual strength retention rate, where the highest retention rate in flexural modulus and flexural were found to be 95.0% and 87.3%, respectively.

Despite the CFRP composite specimens containing conductive nanofillers showed significant improvement in the lightning strike damage tolerance, our investigations showed that the lightning strike damage still cannot be fully eliminated. When compared to the traditional lightning strike protection solution using copper mesh, the solution of using conductive nanofillers is still not mature to date. Moreover, our results showed that adding extensive amounts of conductive nanofillers could lead to adverse effects on the flexural modulus and strength due to the defect formation. Future research is recommended to understand the effect of conductive nanofillers on the microstructure (e.g., porosity, defects) and other mechanical properties (e.g., translaminar fracture toughness, delamination resistance). Moreover, the challenges of increased viscosity and thus the manufacturability with the addition of conductive nanofillers also remain to be solved. Additionally, the trade-off between the performance and cost needs to be properly addressed in future studies.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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