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Coupled Flexural-Electrical Evaluation of Additively Manufactured Multifunctional Composites at Ambient Temperature

Ritesh Ghimire * and Frank Liou

Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA; liou@mst.edu
* Correspondence: rgp2y@mst.edu

Abstract: Multifunctional composites offer a higher strength to weight ratio, electrical properties, etc., thereby providing possible solutions for replacing the physical electrical wirings in aircraft. The lack of research on the coupled multifunctional characterization of 3D printed composites flexural-electrical properties is the main reason for its unsuitability in aerospace applications. The proposed method evaluates multifunctional flexural-electrical properties of 3D printed multifunctional carbon fiber composites. Traditional methods for conducting structural and electrical analyses for aircraft certification do not accommodate new technologies that are not yet proven. Such technologies are additive manufacturing (AM) techniques, multifunctional composite structures, and the certification requirements for 3D printed multifunctional carbon fiber composites for use in aircraft. In this study, the multifunctional 3D printed specimens were concurrently evaluated for flexural-electrical properties using three-point bending and electrical conductivity tests. The results showed that the multifunctional properties included the maximum flexural strength of 271 MPa and the maximum electrical resistance of 55.1 G Ohms, with the failure modes and mechanisms found to be consistent with the traditional composites. Due to its infancy, the existing AM techniques, and the use of the multifunctional carbon fiber composites manufactured using those AM technologies, are not implemented on a large commercial scale.

Keywords: coupled flexural-electrical evaluation; 3D printing; multifunctional composites; continuous carbon fiber solid laminate; ambient temperature testing

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1. Introduction

Traditional monofunctional analyses for unifunctional properties of aircraft structural components made from additively manufactured carbon fiber composites are well addressed and matured through various research and certification requirements. For satellite mass and volume reduction, three-point bending and electrical tests were not conducted concurrently on the traditionally manufactured multifunctional structural battery test specimens (assuming that electrical batteries do not work during satellite launching) [1]. Fused filament fabrication (FFF) is a three-dimensional printing technology with a layer-by-layer construction of an element by continuously depositing thermoplastic material system through a nozzle of the AM machine [2]. The FFF is used for advanced manufacturing of advanced material system with a degree of tailorability compared to the traditional manufacturing techniques [2]. Four-point flexural and tensile tests were conducted on continuous carbon fiber-reinforced composites (CCFRP) test coupons additively manufactured using fused deposition modeling (FDM) [3] to assess monofunctional flexural and tensile properties [4]. FDM was used for 3D printing of the CCFRP with concentric and isotropic carbon fiber infill patterns [4]. The microstructures characterization of the CCFRP composites were conducted using an optical microscope and a scanning electron microscope (SEM) [4]. Structural tests were conducted for assessing the dependency behaviors of the carbon fiber concentration and infill patterns on both flexural and tensile properties [4]. While the test results showed that the coupons with the concentric carbon fiber infill pattern exhibited higher flexural strength and energy absorption capability than those with the isotropic carbon fiber infill pattern, the multifunctional properties, with respect to the coupled flexural-electrical evaluation of additively manufactured multifunctional composites at ambient temperature, was not addressed [4]. The multifunctional properties, such as the flexural and electrical properties on the same component, are not addressed yet. They are not matured, thus needing research to analyze the applications of the coupled multifunctional characterization of the multifunctional composites in the aircraft primary and secondary structures. Monofunctional flexural assessment of traditionally manufactured composites using a three-point bending test, and failure analysis using a scanning electron microscope, were conducted [5]. Quasi-static rate of 1 mm/minute was used for in-situ three-point bend tests on glass/epoxy (GE) and carbon nanotubes embedded glass/epoxy (CNT-GE) composites at ambient condition (20 °C), 70 °C, 110 °C, −80 °C and −40 °C [5]. The experimental results showed that the flexural strength of GE and CNT-GE composites at 110 °C was significantly decreased by 67% and 81%, respectively, compared with their strength at −80 °C [5]. Similarly, 38% and 77% decrease in modulus values were observed for the GE and CNT-GE composites, respectively [5]. Post failure analysis of the fractured specimens was conducted to evaluate various possible failure modes and failure mechanisms using the SEM [5]. Since the scope of this paper was limited to monofunctional composites manufactured using the traditional hand layup method, this paper did not address the multifunctional properties of the 3D printed multifunctional continuous carbon fiber solid laminate composites. Monofunctional three-point bending flexural testing was conducted on continuous glass-fiber reinforced thermoplastic composites test coupons, manufactured using laser-assisted AM technique [6]. Laser assisted AM technology utilized glass fiber (GF)-polypropylene (PP) prepreg composites for manufacturing test coupons by using laser assisted bonding and laser cutting [6]. GF/PP prepreg composites were added in successive layers, and 3D model was chopped into various 2D slices with each slice then sliced using associated 2D slice [6]. This process was repeated using a layer-by-layer approach to achieve a complete solid laminate in 3D model as defined per CAD file [6]. A pregpreg was used as the first and base layer in the article as a substitue for the narrow cut tape for higher quality bonding for the solid laminate [6]. Laser and compaction roller were used for layer-by-layer placement of the tape strips. The CO_2 laser (with 100 W max. power) was emitted at the interface of two layers with 18° angle from the base prior to putting pressure via compaction roller to combine the prepreg [6]. The roller, laser beam, and mirrors were stationary in tape placement process, and the prepreg was provided under the compaction roller utlizing a motorized stage [6]. Process parameters for feeding the tape below the roller were laser power of 22–28 W and the speed of stage movement of 1–4 mm per second [6]. The fine shape was cut using full spectrum laser with 90W maximum power after getting a 2D shape profile [6]. The laser cutting process parameters of 31.5 W power, 70 mm/s cutting speed, and 1 mm spot diameter, which involved a 3D printed article to move back and forth between two stations [6]. While the microstructure, characterized by SEM, showed superior bonding of prepreg layers with no visible void or gap, which is substantially improved compared to other AM techniques such as FDM, the multifunctional properties on the 3D printed continuous carbon fiber solid laminate test coupons were not addressed [6]. This paper was limited to evaluation of the monofunctional property and its structural performance.

Composites made up of polyamide 6 (PA-6) polymer films and conductive polyaniline (PANI) particles were chemically investigated by in-situ polymerization of aniline inside the PA-6 matrix at ambient temperature for surface electrical conductivity evaluation [7]. This study measured the frequency dependence of permittivity of these antistatic polymer films [7]. Surface electrical conductivity was measured by utilizing the potential decay technique [7]. While it was found that the improved surface electrical conductivity initiated by percolation of PANI phase in the surface layer of PA-6 films, this study did not address the coupled flexural-electrical evaluation of 3D printed multifunctional composites [7]. Mechanical and electrical properties of polyamide 6/graphene nanoplatelet composites manufactured using melt processing via twin-screw extrusion were evaluated [8]. Graphene nanoplatelets (GNPs) were used to examine the influence of particle dimensions on composite properties [8]. While the electrical conductivity and the increase in the weight fraction of GNPs were directly proportional that resulted in an increase of six orders of magnitude on the addition of up to 15 wt% GNPs, this study did not address multifunctional properties (coupled flexural-electrical) evaluation of 3D printed multifunctional carbon fiber composites [8]. The electrical, thermal, and mechanical properties of additively manufactured PA6 nanocomposites were investigated for electrostatic discharge applications [9]. Fused deposition modeling (FDM) was used for test samples fabrication, and it was found that the flexural properties were improved by 3 wt% addition of carbon nanofiber (CNF) with no enhancement observed at 5 wt% CNF [9]. While the volume resistivity of the PA6 matrix was significantly reduced due to the addition of 3 wt% and 5 wt% CNF which seemed to have potential use for static discharge products, this study did not cover the multifunctional properties of 3D printed continuous carbon fiber composites [9]. Monofunctional electrical and tensile properties of injection-molded multiwalled carbon nanotubes (MWCNT) reinforced polyamide 66 hybrid composites were investigated in which the chopped carbon fiber of different lengths and the MWCNTs were added to nylon 6,6 [10]. The monofunctional electrical conductivity test was completed on the same test coupons before the tensile testing [10]. While the test results depicted the excellent electrical properties due to the addition of fillers with a limitation in mechanical properties improvement, this study did not address the multifunctional coupled flexural-eletrical properties of the 3D printed continuous carbon fiber composites [10]. Multi-functional composites were manufactured, which involved introducing carbon nanotubes (CNTs) into carbon fiber wet-laid composites as functional nano-fillers for improved electrical, thermal, and mechanical performance [11]. Polyamide 6 (PA6) short fiber was introduced into carbon fiber and CNT mixture to improve bonding between CNTs and the carbon fiber [11]. While the addition of CNT to the carbon fiber nonwoven and the electrical conductivity were observed to be directly proportional to each other and a slight decrease in tensile strength, this paper did not address the coupled multifunctional flexural-electrical properties of the 3D printed continuous carbon fiber composites [11].

There are no current solutions to certify multifunctional carbon fiber composite structures for an aircraft. Existing manufacturing techniques from the unifunctional composites material system to support the coupled multifunctional carbon fiber composites have not been investigated. The maturation of existing manufacturing techniques for implementation into the aircraft and its certification tests are needed. Due to the infancy of the existing AM techniques and processes, those technologies are not used in aerospace applications. The multifunctional carbon fiber composites are not implemented on a large commercial scale in aircraft, unmanned aircraft systems (UAS), and spacecraft. Limited studies are available in the literature on the use of the AM technologies and the multifunctional evaluations of multifunctional composites. The existing regulatory frameworks, policies, guidance, and industry consensus standards pertain to monofunctional material systems. An experimental investigation was performed for the assessment of electro-flexure response of the conductive natural fiber hybrid composites that were made up of laminates of jute and flax fibers [12]. Test coupons were tested to undergo flexural loading for the electrical and bending responses [12]. Four-point circumferential probe method was utilized for measuring electrical response exerted by flexural loading of the test coupons [12]. Varying carbon fiber lengths and carbon fiber densities were used for comparative assessment of flexural performance, and deformation detection revealed that an increase of carbon fibers decreased the flexural strength and increased the flexural strain at break for all composites of carbon fiber length of 150 μm [12]. While the concurrent electro-flexure response was conducted on the traditionally manufactured solid laminate composites, the coupled multifunctional properties of additively manufactured multifunctional composites are not addressed to date [12]. Certification requirements for composite aircraft are separate for assessing the monofunctional properties (e.g., electrical, thermal, structural, etc.). Those monofunctional properties are known as unifunctional material system properties. Three-point bend testing was conducted on traditionally fabricated multifunctional carbon nanotubes, enhanced structural composites for improved toughness, and damage monitoring. Reinforcement effects of the multifunctional carbon nanotubes enhanced structural composites were structurally investigated via tensile and three-point bend testing, which led to significant improvement of stress and strain at failure [13]. This study also included the assessment of the structural health monitoring capability via the use of quantum resistive strain sensors made up of carbon nanotubes filled epoxy nanocomposite embedded at the core of the glass fiber-epoxy composites [13]. While the electrical characterization is mentioned, the electrical conductivity is not included in this research [13]. Also, the coupled flexural-electrical evaluation of additively manufactured multifunctional composites at ambient temperature was not addressed [13]. Flexural properties were characterized using three-point bending tests on continuous carbon-fiber reinforced thermosetting composites prepared using the FDM AM technique [14]. The 3D printed thermosetting composites' flexural performance was found to be superior to similar 3D printed thermoplastic composites, and 3D printed short carbon fiber-reinforced composites in [14]. Coupled effects of the multifunctional properties such as flexural-electrical properties of the 3D printed multifunctional continous carbon fiber solid laminate composites were not addressed [14]. Monofunctional flexural strength test was conducted on a novel 3D printing-based fabrication process of continuous fiber reinforced thermoplastic composites in [15]. Continuous carbon fiber was chosen as a reinforcing phase and PLA filament was chosen as matrix, and both the continuous carbon fiber and the PLA filament were simultaneously fed into the FDM 3D printer to develop an integrated continuous fiber reinforced thermoplastic composites [15]. The process parameters on temperature and pressure were analyzed for performance and interfaces of 3D printed coupons [15]. It was observed that the fiber content of the printed specimens is a function of the process parameters that exhibited flexural strength of 335 MPa and modulus of 30 GPa for the fiber content of 27% [15]. While the study found that the 3D printed continuous fiber composites is dependept on the fiber content, the multifunctional flexural-electrical properties and their coupling effects on the 3D printed continuous carbon fiber solid laminate composites were not included in [15]. The continuous carbon fiber-reinforced polylactic acid composite was manufactured using 3D printing to evaluate coupons' flexural strengths [16]. The comparative analysis of 3D printed coupons with or without preprocessed carbon fiber bundle was performed for measuring the improvement of the proposed method [16]. The mechanical strength was measured [16]. While the test results exhibited higher tensile strength and flexural strengths compared to the original carbon fiber reinforced test coupons, this paper did not address the coupling effects of the multifunctional properties in flexural-electrical mode of the 3D printed continuous carbon fiber solid laminate composites [16]. Flexural properties of the test coupons fabricated using material extrusion AM of endless carbon fiber-reinforced composites were investigated to assess the influence of layer height and width on mechanical properties [17]. The composites with two different 3k carbon fibers as reinforcements are 3D printed by material extrusion technique with various layer heights and layer widths [17]. Experimental results exhibited that the composites ganerated higher flexural strength at smaller layer height and the flexural modulus was dependent on the fiber volume content of the 3D printed composites [17]. The structural properties were decreased by the formation of delamination and voids that required further optimization [17]. The coupled flexural-electrical evaluation of the additively manufactured multifunctional continous carbon fiber solid laminate composites at ambient temperature was not addressed [17]. While there have been several recent studies on the use of the FFF for manufacturing 3D printed composites using advanced material systems, such as the thermoplastic Ultem 9085, conducted at the premier applied research institute (the National Institute for Aviation Research (NIAR)), the coupled flexural-electrical evaluation of 3D printed multifunctional composites at ambient temperature was not addressed [18]. Ultem 9085 is a thermoplastic material that can be processed by FDM, has great good structural properties, flame retardancy and low smoke generation [19]. Both the thermal and mechanical properties of Ultem 9085 was conducted [19]. The flexural and tensile tests were conducted on Ultem 9085 resin test coupons manufactured using FDM, with varying building orientations [19]. While the test results show the great structural properties of Ultem 9085 built to XZ orientation and confirm that the building direction has a significant effect on tensile and flexural properties, this study did not address the multifunctional properties of the 3D printed continuous carbon fiber composites [19].

A recent study on electro-mechanical effects of the multifunctional carbon fiber reinforced polymer composite structures was investigated to evaluate the effects of electric current and dynamic mechanical properties of the multifunctional composites [20]. It was found that if carbon fibers were used as the multifunctional parameter for both the reinforcing and sensing functions, and a low current was applied (~100 mA), then the mechanical properties of the multifunctional carbon fiber composites were not changed [20]. The effects of electric current connected to multifunctional carbon fiber regarding the traditionally manufactured composites' dynamic flexural properties were conducted in [20]. Tests results concluded a current limit of 0.5 A due to heat generation issues and no fluctuations on flexural properties, with varying amperage and connection time of the current applied to test coupons [20]. Traditional methods of conducting separate flexural and electrical tests to support the certification tests of an aircraft do not address the new technologies like additively manufactured multifunctional composites. The multifunctional characterization of the multifunctional continuous carbon fiber solid laminate composites is not addressed. Traditional means of compliance and method of compliance from [21] are not understood to support the certification tests for the coupled multifunctional flexural and electrical properties of the AM multifunctional composites. Thus, in this work, the coupling effects of the flexural and electrical properties of the additively manufactured multifunctional continuous carbon fiber solid laminate composites on the same component are investigated using the flexural-electrical testing at ambient temperature with the hope of a weight reduction of aircraft, UAS and spacecraft. These tests are repeated for different test coupons at ambient temperature conditions to simulate the real situations of aircraft, UAS, and spacecraft.

2. Materials and Methods

2.1. Material Design and Selection

The multifunctional carbon fiber composite material systems were designed by selecting the raw material manufactured by Markforged Company (Watertown, MA, USA) [22] to characterize flexural and electrical performance's coupled multifunctional properties. The selection criteria for choosing the carbon fiber are that the carbon fiber provides the best strength in the longitudinal direction and also a carbon fiber is the most commonly used in aerospace applications due to its higher strength to weight ratio.

2.2. Additive Manufacturing for Fabrication

The solid laminate test specimens and coupons were additively manufactured using a Markforged 3D printer at RE3DTECH company based in Grayslake, IL, USA, with a raster angle of 0 degree. The fused filament fabrication (FFF) AM technique was used. Onyx with continuous carbon fiber (Onyx FR) manufactured by Markforged company was used. Onyx is a micro carbon fiber filled nylon, and is 1.4 times stronger and stiffer than ABS and can be reinforced with any continuous fiber [23]. Onyx sets the bar for surface finish, chemical resistivity, and heat tolerance [23]. The Onyx FR is a UL 94 V-0 Blue Card certified down to a thickness of 3 mm [24]. The selection of the applied process parameters and the printing conditions was such that the continuous carbon fiber solid laminate had to be 3D printed via dual nozzles using Markforged continuous filament fabrication (CFF) for the additive manufacturing of the test coupons. Rationalization of the selection of the process parameters for this study entailed achieving the consistent and repeatable fabrication of the 3D printed multifunctional continuous carbon fiber solid laminate test coupons. Another reason for the selection of the process parameters was to ensure that there were negligible defects compared with the traditionally manufactured carbon fiber composites. A fused filament fabrication (FFF) known as Markforged company's continuous filament fabrication (CFF) was used in this study as the optimized printing conditions for this study's 3D printing of test coupons. Process parameters for the 3D printing were as follows: Onyx printing nozzle temperature of 275 °C, and the fiber laying nozzle temperature of 250 °C. The diameter of the extruded fiber material was 0.9 mm wall thickness and that of the extruded Onyx material was 0.40 mm wall thickness. An additional consideration for the selection of process parameters in this study was that the 3D printed coupons had to be 3D printed with multifunctional continuous carbon fiber solid laminate composites. The main reason for the selection of the continuous carbon fiber solid laminate composites is that the carbon fiber offers the maximum strength along the fiber direction. The most important parameter was that all the coupons had to be 3D printed in a uniform and consistent manner to reduce the variability due to environmental effects and material and processing.

2.3. Environmental Conditioning and Ambient Testing

A room temperature dry (RTD) method was chosen for this investigation as the environmental conditioning and nonambient testing profile to assess the multifunctional behavior of flexural and electrical properties of the test coupons as a baseline. AGATE-WP3.3-033051-102 was used as a reference for environmental conditioning and nonambient testing profile of test coupons as shown in [25].

2.4. Multifunctional Flexural-Electrical Characterization

Electrical properties assessment and flexural properties were conducted concurrently while the test specimens were subjected to electrical conductivity and flexural tests. This test was conducted by connecting the two ends on the samples with a spacing of 49 mm, with a Keysight B2987A Electrometer (Keysight Technologies, Santa Rosa, CA, USA) to measure the electrical conductivity from end to end along the carbon fiber direction when exerted under flexural loadings. A three-point bending test was used for flexural properties assessment per ASTM D7264-15 [26]. A test rate of 0.00127 m/minute was used to conduct the flexural testing. The testing temperature was ambient, and relative humidity for the testing was ambient. Dimensions of the 3D printed test coupons were 140 mm × 13 mm × 3 mm. The average distance between the electrical contacts was 49 mm. The test coupons' coupled effects were measured using instrumentation and then computed for electro-flexural properties. After every 18 N, the electrical resistance of test coupons was measured until the test coupons failed. A schematic detail of the multifunctional flexural-electrical characterization test at RTD is shown in Figure 1. Similarly, the failure modes of the test coupons after the multifunctional flexural-electrical characterization test at RTD are shown in Figure 2. Lateral failure mode was observed on the test coupons with respect to its longitudinal axis on the lower side in the outer fibers. Resistance measurements were taken every 18 N until the failure of the test coupons. The maximum resistance value was chosen that occurred during the testing of coupons.

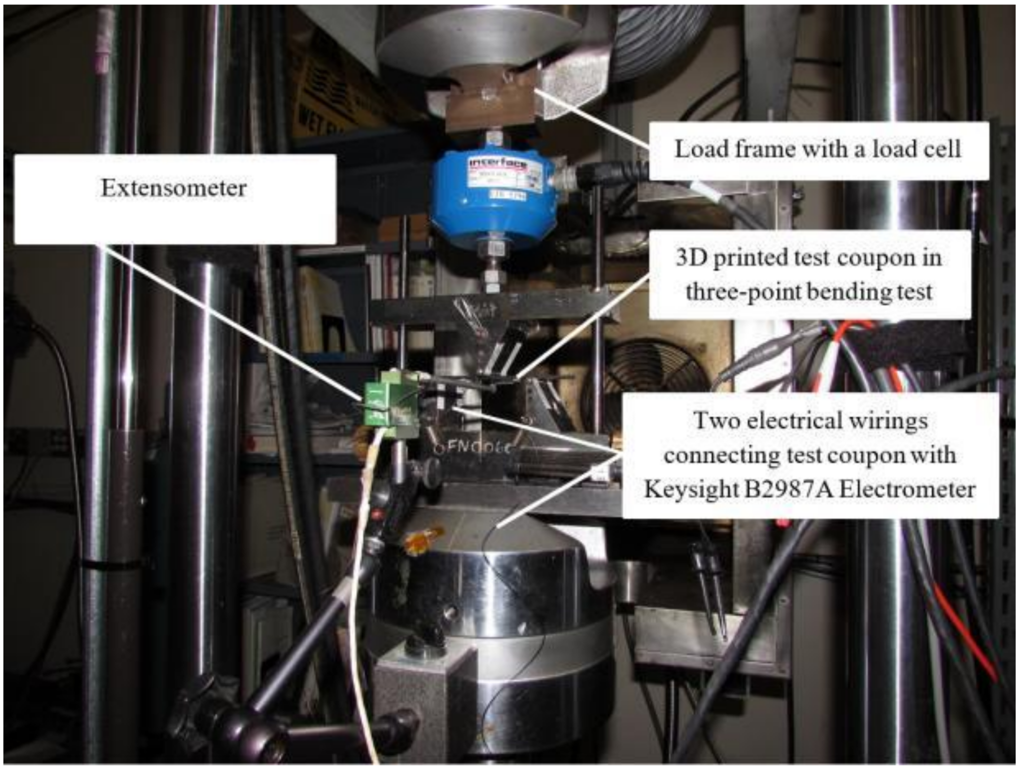


Figure 1. Schematic details of the multifunctional flexural-electrical characterization test at RTD.

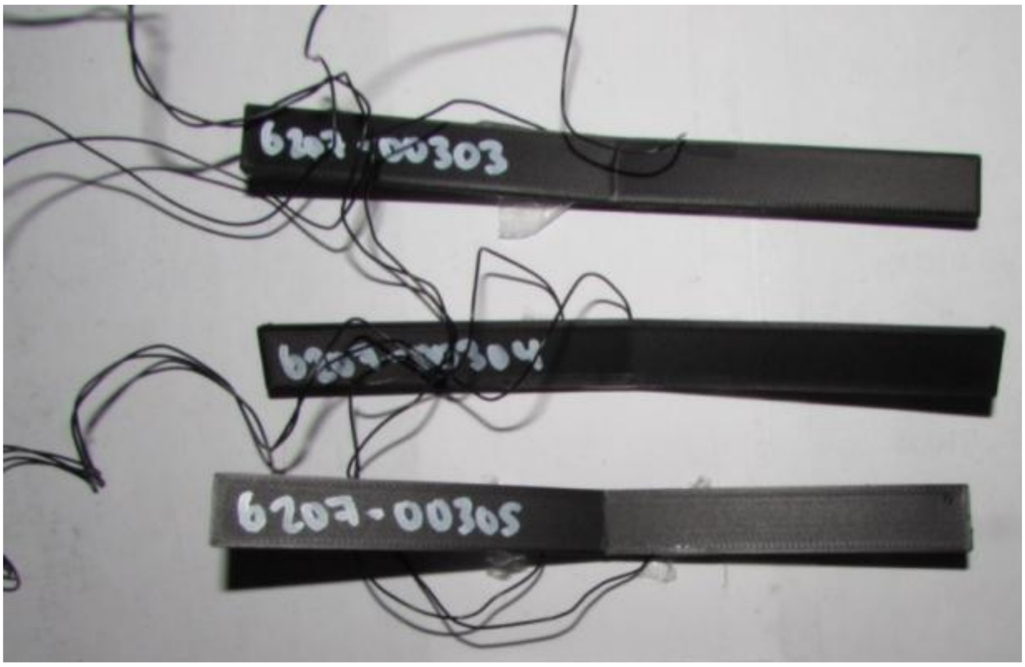


Figure 2. Failed test coupons after the multifunctional flexural-electrical characterization test at RTD.

3. Results and Discussion

The multifunctional flexural-electrical performance of 3D printed composite coupons was characterized using a mechanical testing machine and a Keysight B2987A Electrometer. The experimental results showed that the test specimen exhibited an ultimate load of 178.7 N with a corresponding maximum deflection of 0.0089 m, a corresponding maximum flexural stress of 271 MPa, and a maximum strain of 0.0202 m/m. The reported value of the maximum flexural stress was 271 MPa with the maximum strain of 0.0202 m/m.

The recorded maximum resistance was 55.1 G Ohms as a multifunctionality property. As shown in Figure 2, a lateral tensile failure mode that is perpendicular to the longitudinal axis of the coupons was induced along its lower side in the outer fibers of the test coupons. This failure mode was found to be consistent with the failure mode from the flexural testing of the monofunctional carbon fiber composites conducted at an ambient temperature. This harmony of the failure modes of the 3D printed multifunctional continuous carbon fiber composites and that of the traditionally manufactured carbon fiber composites suggests that the multifunctional continuous carbon fiber composites are suitable for structural applications in aerospace. Figures 3–5 summarize the multifunctional performance of the 3D printed continuous carbon fiber solid laminate composites test coupons. Figure 3 shows the loading versus time, and Figure 4 shows stress versus strain, while Figure 5 shows resistance versus strain of the test coupons.

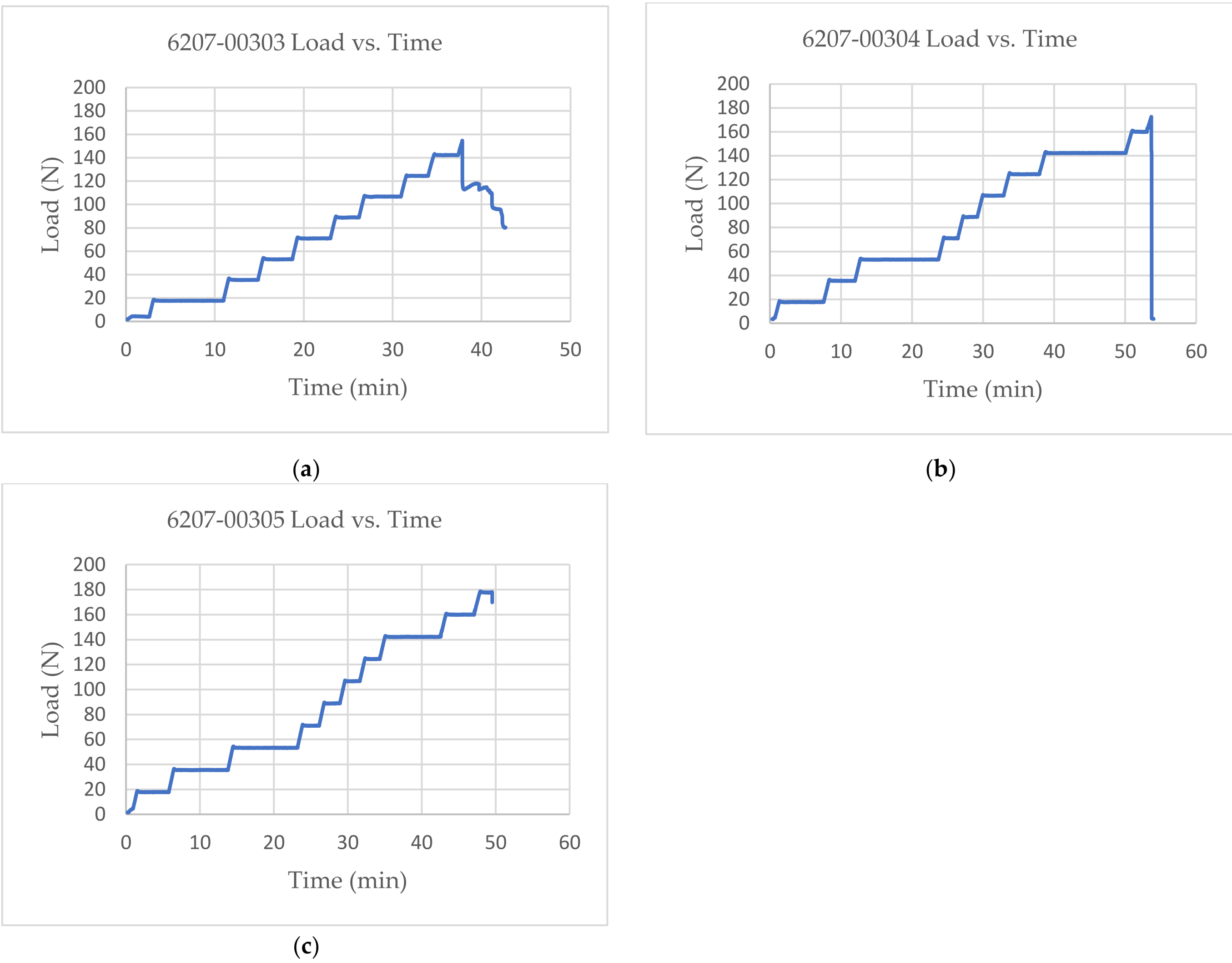
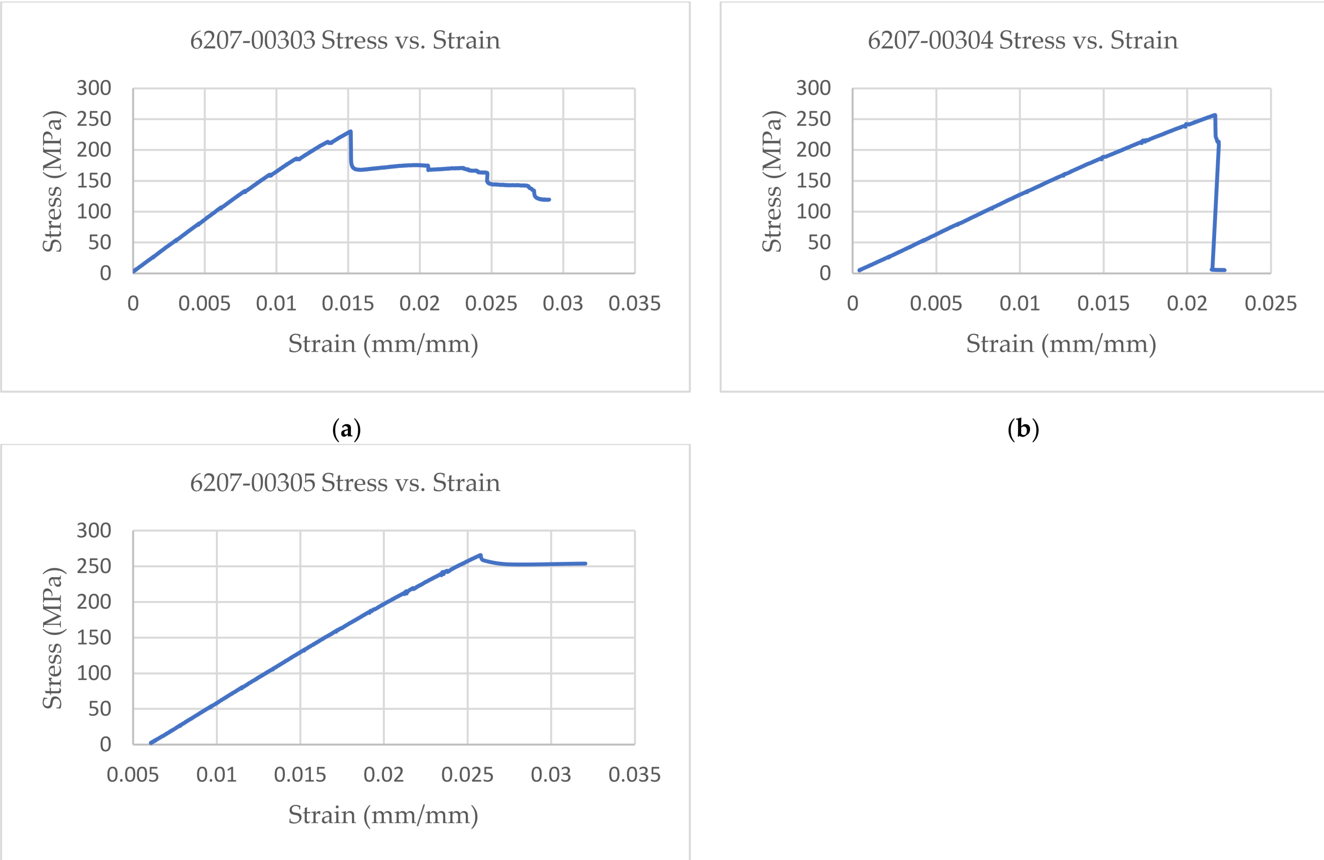


Figure 3. Loading versus time behavior of multifunctional test coupons at RTD: (**a**) 6207-00303; (**b**) 6207-00304; and (**c**) 6207-00305.

Figure 3 shows the loading versus time behavior of the 3D printed multifunctional continuous carbon fiber composites test coupons at RTD with step-wise function of loading on time scale to depict the time required for the electrometer settling times. The settling times are defined as the times it takes to settle and calm the fluctuations of the oscillations on the electrometer. The settling times needed for this study could have been attributed to the fact that the test coupons are highly resistive in nature. The loading versus time behavior of the 3D printed multifunctional continuous carbon fiber composites was also analyzed to assess the effects of the settling times on the failure loads of the test coupons.



(**a**) (**b**) (**c**)

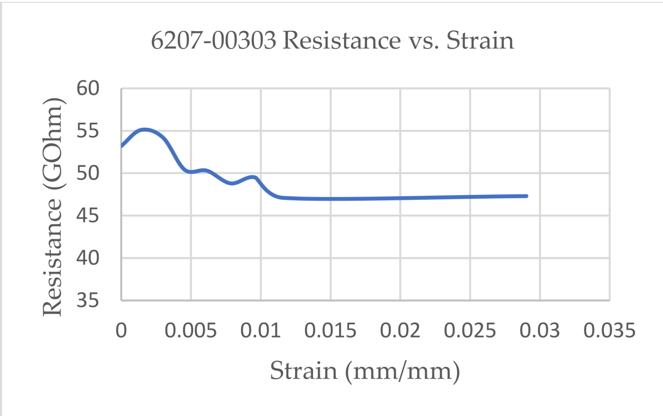
Figure 4. Strain-strain behavior of multifunctional test coupons at RTD: (**a**) 6207-00303; (**b**) 6207-00304; and (**c**) 6207-00305.

Figure 4 shows the strain-strain behavior of the 3D printed multifunctional continuous carbon fiber composites test coupons at RTD. It was found that the stress-strain performance of the 3D printed multifunctional continuous carbon fiber solid laminated composites is consistent with the stress-strain behavior of the traditionally manufactured carbon fiber solid laminate composites. The maximum flexural stress of 271 MPa and the maximum ultimate load of 178.7 N were induced by 6207-00305.

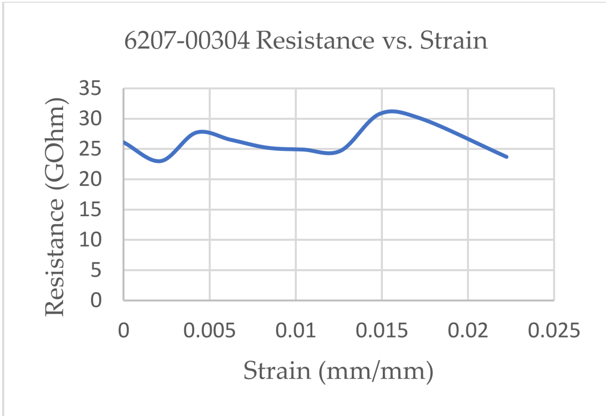
Table 1 summarizes the experimental test results with an average maximum flexural stress of 247 MPa and an associated maximum strain of 0.0195 m/m. The experimental test results showed that the 3D printed solid laminate test coupons exhibited an average ultimate load of 168.7 N and contributed to an average deflection of 0.0085 m at the ultimate load (as shown in Table 1). Table 2 shows the summary of the maximum resistance values of each test coupon at the RTD.

As shown in Figure 5, the strain corresponding to the peak resistance value for 6207-00303, 6207-00304, and 6207-00305 was higher than the failure strain on each of those test coupons. Similarly, the strain at peak resistance value when compared to the respective failure strain was found to be 95.11% higher than the corresponding failure strains for test coupon 6207-00303. The strain associated with the peak resistance value for test coupon 6207-00304 was found to be 81.02% higher than the corresponding failure strain for test coupon 6207-00304. The strain associated with the corresponding failure strains for test coupon 6207-00305 was observed to be 64.13% higher than the corresponding failure strains for test coupon 6207-00305. The resistance values during the tests were found to be higher than the residual resistance values for the one test coupon (6207-00304) and were lower than the resistance values for the other two test coupons (6207-00303 and 6207-00305).

For test coupon 6207-00305, the residual resistance value (41.5 G Ohms) was found to be higher than the values recorded during the tests (37.6 G Ohm, 9.40% lower than 37.6 G Ohms). This may be attributed to material and manufacturing defects. Thus, the reported coefficient of variation (COV) in Table 2 is higher. The slight variation in the values could have been contributed by the lack of electrical shielding as well as the difficulty on the MTS machine to add the electrical shielding system. Resistance versus strain behavior of the test specimens was found to be stable with a small degree of fluctuations. This small degree of fluctuation may have been contributed to by the underlying coupled compression on the top of the coupons and the tension on the bottom of the test coupons while the specimens underwent multifunctional testing.



(**a**)



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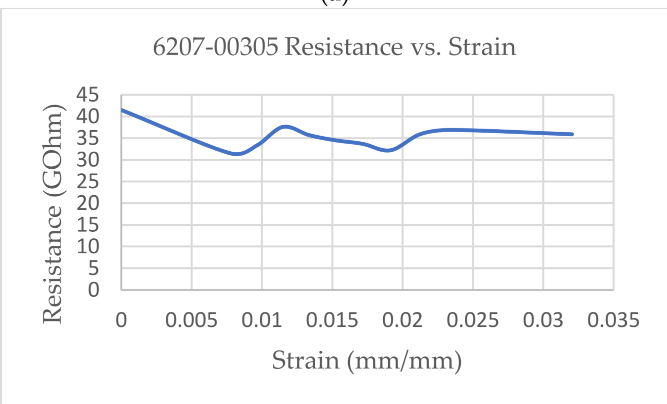

(**c**)

Figure 5. Multifunctional flexural-electrical performance of test coupons at RTD: (**a**) 6207-00303; (**b**) 6207-00304; and (**c**) 6207-00305.

Table 1. Summary of results of test specimens.

Coupon ID	Ultimate Load (N)	Deflection at Ultimate (m)	Maximum Flexural Stress (MPa)	Maximum Strain, ε
6207-00303	154.7	0.0069	204	0.0166
6207-00304	172.6	0.0097	268	0.0218
6207-00305	178.7	0.0089	271	0.0202
Average	168.7	0.0085	247	0.0195
Standard Deviation	12	0.0015	38	0.0026
Coefficient of Variation (COV)	7.4%	17.3%	15.3%	13.4%

Table 2. Summary of maximum resistance values of test specimens.

Coupon ID	Maximum Resistance (G Ohms)
6207-00303	55.1
6207-00304	30.8
6207-00305	41.5
Average	42.5
Standard Deviation	12.18
Coefficient of Variation (COV)	28.68%

The linear and non-linear deformations of the 3D printed continuous carbon fiber composites specimens contributed to the slight rise and decrease in electrical resistance property of the test coupons from one layer to another. The onyx coating of the continuous carbon fiber strand also played a vital role in small fluctuations from layer to layer as the specimens underwent multifunctional testing at RTD. The failure modes of the tested coupons, as shown in Figure 2, suggest that the multifunctional flexural-electrical characterization performance at RTD is consistent with the traditional carbon fiber composites. The lack of delamination and voids in the 3D printed coupons compared to the traditional hand-laid up composites may have also contributed to a small degree of fluctuations in the electrical resistance property along the strain variations. Thus, the coupled flexural-electrical evaluation of 3D printed multifunctional composites at ambient temperature proves suitable for aerospace applications. This experimental investigation and its results suggest that the 3D printed continuous carbon fiber solid laminate composites exhibit a multifunctional property appropriate for aircraft, UAS, and spacecraft applications.

4. Conclusions

This study investigated a new and novel method to evaluate the coupled multifunctional electro-flexural properties of the additively manufactured multifunctional continuous carbon fiber solid laminate composites at ambient temperature. In this study, a new multifunctional test method was proposed to address the coupling effects of the two unifunctional properties (electrical and flexural) in the same component simultaneously. Test coupons were manufactured using a 3D printing technique for printing continuous carbon fiber solid laminate composites. The experimental results showed that the test specimens exhibited average values of ultimate load of 168.7 N with a corresponding deflection at an ultimate load of 0.0085 m, while the average maximum flexural stress was 247 MPa, and the maximum strain was 0.0195 m/m. The reported maximum flexural stress is 271 MPa and the associated maximum strain is 0.0202 m/m. The observed maximum resistance during the multifunctional testing was 55.1 G Ohms (as the multifunctionality property in this investigation). The resistance versus strain behavior of the specimens were shown to be stable, albeit with a small degree of fluctuations that are contributed by the underlying coupled tension effects on the top of the coupons and the compression effects on the bottom of the same test coupons while the specimens underwent the multifunctional testing at the RTD. This study also showed that the coupons' deformations were the contributing factors for small fluctuations in electrical resistance values of the specimens from one layer to another. Another contributing factor for that small fluctuation is the onyx coating of the continuous carbon fiber strand. As the combination of tensile and compressive forces are exerted on the different layers, the onyx coating acts as an insulating agent and thus leading to an increase in resistivity. The residual resistance value of at least 25 plus G Ohms on the test coupons as depicted in the plots of resistance versus strain showed that the test articles can be optimized and tailored to achieve desired multifunctional properties (as both the structural and electrical). Selection of the coating material will play a significant role in optimizing the multifunctional properties of the 3D printed continuous carbon fiber solid laminate composites. This study also investigated the failure modes and mechanisms of the tested coupons. Those results suggest that the multifunctional electro-flexural characterization at RTD is consistent with the failure modes of the traditionally manufactured carbon fiber composites and that they agree well with the traditional composites failure modes. This agreement with the traditional failure modes signifies the importance of this new and novel method for assessing the multifunctional properties of the 3D printed continuous carbon fiber solid laminates. The relatively negligible amount of delamination and voids in the 3D printed coupons compared to the traditional hand-laid up composites may have also contributed to that small degree of fluctuations in the electrical resistance property along the strain variations. Thus, this investigation's findings suggest that the 3D printed continuous carbon fiber solid laminate composites exhibit a multifunctional property appropriate for aircraft, UAS, and spacecraft applications due to their practicality and significant weight-savings potential.

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