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Higher strength carbon fiber lithium-ion polymer battery embedded multifunctional composites for structural applications

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Abstract

This study proposes and evaluates the structural integrity of a carbon fiber reinforced polymer (CFRP) composite containing encapsulated lithium-ion polymer (Li-Po) batteries. A comparison of various composite structures made of CFRP having the core of lithium-ion batteries is conducted. Electrospinning is globally recognized as a flexible and cost-effective method for generating continuous nanofilaments. In this study, epoxy-multiwalled carbon nanotubes (CNT/epoxy) were electrospun onto CFRP layers, which improved interfacial bonding and strong adhesion between the layers which ultimately worked as an effective packaging for Li-ion batteries. This composite structure showed enhanced mechanical strength compared to the standard CFRP laminate structure due to incorporating electrospun CNT/epoxy nanofibers in between the layers. An alternate method was proposed for comparison where CNT/epoxy was air sprayed onto the CFRP layers. CFRP structure containing airsprayed CNT/epoxy was found to be stronger than standard CFRP laminate structure, although not as strong as electrospun CNT/epoxy enhanced CFRP laminates. Finally, the design validation, manufacturing method, and electromechanical characterization of multifunctional energy storage composites (MESCs) were examined and compared. Electrochemical characterization showed that MESCs with electrospun CNT/epoxy nanofibers enhanced CFRP laminate under loading conditions had similar performance to the standard lithium-ion pouch cells without any loading. The mechanical robustness of the proposed CFRP composite structures enables their manufacturing as multifunctional energy-storage devices for electric vehicles and other structural applications.

KEYWORDS

electrospinning, multifunctional carbon-fiber composites, structural battery, mechanical and electrical properties of CFRP

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1 | INTRODUCTION

Carbon fiber reinforced polymer (CFRP) laminates and sandwich composites are increasingly being used to produce lightweight motor vehicles to minimize fuel consumption and greenhouse gas emissions. Researchers and commercial sectors have become more focused on structural weight and volume deduction approaches to solve issues such as improved fuel efficiency to decrease CO₂ emissions in structural applications involving aircraft, spacecraft, and commercial vehicles.^{1–3} CFRP composites, along with battery integration, are increasingly being used in structural sections of automobiles, such as body panels and chassis, to achieve this goal of reducing the cost of fuel consumption and greenhouse emissions.^{4,5} These structural batteries, which are incorporated with energy storage functionality, could help in reduction in weight and volume.^{6,7} The packaging material is critical for load-carrying capacity in the existing structural batteries.^{8,9}

As the automotive industry progresses toward electric propulsion and demand for hybrid and electric vehicles increases, issues for energy storage in these vehicles emerge in terms of vehicle space. This impacts the vehicle's empty weight as the battery system weighs up to 37% of the overall curb weight, requiring a larger volume storage area.^{5–7} The use of multifunctional composites in vehicle components is a requirement for the structural and spatial integrity of the vehicle.^{4,10–12} Electrical storage devices can be integrated into composite structures by using different approaches. The structural dielectric capacitor (SDCs) is a composite energy storage manufacturing approach where carbon fibers function as electrodes and bear the structural loads.¹³ This approach could utilize a multifunctional material that serves as an electrical energy storage device and load bearer. In another approach, composite materials are used in embedding the battery pouches independently. These integration approaches allow the composite structure to provide energy storage and load carrying capability.^{9,13–15} Compared to traditional batteries, these strategies help save space.⁷

Incorporating batteries into composite materials to create lightweight energy storage structures is a promising approach for the next automobile generation. One such leading energy storage device is the lithium-ion battery. Multifunctional composite structures (MSC) combine high energy storage capacity, that is, li-ion battery or supercapacitor, with superior mechanical properties. Although these Li-ion batteries have a higher energy density and can maintain intermittent charging with fast charge–discharge rates,¹⁶ contamination from the Li-ion pack might cause it to catch fire and explode. The reason

for this is that the moisture in the cell has not dried thoroughly, resulting in a side reaction that generates gas inside the cell, which activates the safety valve. The battery cap's seal is inadequate; a short circuit or leakage of the battery inside or outside may cause a fire as the battery pack is close to the fire source, and the packing material is not fireproof. With this, the use of the Li-ion has been limited for different applications. However, a better structural storage capability could help utilize the Li-ion's advantages.^{17–19} The dynamic and mechanical characteristics of the carbon fiber laminates and their use as energy storage devices have been studied in several publications.^{16,20–23} The research found that when batteries are placed inside composite materials, their bending stiffness increases, lowering the failure stress. This process of embedding necessitates a thorough grasp of mechanical characteristics. The increase in bending stiffness was attributed to arithmetical stress concentration caused by the embedded battery's non-uniform thickness and the weak interfacial contact between the composite laminate and the battery. This process of embedding necessitates a thorough grasp of mechanical characteristics. Experiments revealed that batteries placed in the core of composites as a sandwich have adverse effects on in-plane compression properties due to the regular exposure to static and dynamic compression loads¹⁶; understanding the effects of compressive stress loading on laminate mechanical properties is critical for energy storage and vehicle performance. Carbon nanotubes (CNT)/polymer-based nanocomposites are investigated and found that such composite materials have higher flexural strength with the great potential to be reinforced in carbon fiber laminates.^{24–26} The insertion of Li-ion batteries reduces the failure stress, fatigue life, and compression modulus of CNT/epoxy based CFRP laminates; however, integrating the storage battery within the core of CNT/epoxy laminates stores energy and saves dimensions.^{20,27–29} The magnitude of the cutback varies depending on where the batteries are inserted concerning the direction of compression load. The compression properties were reduced the least when the batteries were stacked perpendicularly to reduce the drop within the load-carrying range of the composite material. Compared to a single battery connected with the same stacking sequence, stacking numerous batteries in the way of loading can result in higher energy storage capacity and save significant space.^{20,27}

Thin-film batteries (TFBs) have been a recent focus of numerous researchers for energy storage composite constructions with a thickness of 1 mm that can be impregnated in a composite laminate without causing substantial structural changes. They can be shaped into more intricate designs than traditional pouch cell

batteries, although of less capacity.^{30,31} CFRP prepregs and glass fiber reinforced polymer (GFRP) prepregs were used in designing the TFBs.^{30,32} TFBs are typically sandwiched between the prepreg material layers and inkjet-printed onto a solar cell in these designs. Laminates contribute to the overall cohesiveness of this sample, and the laminates are then cured at high temperatures and under high pressure. A complementary manufacturing technique is using adhesives to glue the laminates and TFB's together. This approach can be utilized to build an energy storage device by gluing actuators, supercapacitors, or even flexible solar panels to a fiberglass substrate with two-part epoxy.^{33,34} Bonding electronic layers on composite laminates is an alternate method. TFBs are used with piezoceramics to create self-charging composite structures in addition to solar cells.³⁰ Multifunctional composites with incorporated Li-ion bi-cells are another structural energy storage composite; three electrodes are used in this design. The anode in the center sandwiched between two cathodes can be designed into energy storage composites using two approaches: the first uses a stack of bi-cells vacuum-sealed in aluminum packaging or CFRP laminates, and the second uses stacked bi-cells at the center of the sandwich structure.³⁵ However, in both methods, the mechanical robustness of the structure deteriorates significantly.

For manufacturing purposes, bi-cells can be adhesively bonded to the laminates. Contemporary Li-ion batteries are primarily designed for maximum energy storage performance, resulting in low mechanical load-carrying capacity and strength.^{4,36–39} Li-ion pouch cells are made up of alternating cathode and anode layers separated by membranes composed of thin microporous polymers. Copper and aluminum are used to make sophisticated thin paper electrode films with a high structural composition.^{37,40} The layered current collectors are stacked loosely, which leads to less load transfer and mechanical bonding between the layers. Even the slightest mechanical pressure exerted induces unnecessary deformation and layer sliding when these pouch cells are bent. Vacuum-sealed aluminum–polymer–laminate is used for the packaging. As a result, the structure's strength is modest.

Herein, the fabrication of structural load-bearing batteries using MESC as an alternate technique is investigated. MESCs are a new energy storage device with high mechanical strength and yet they are lightweight and have good energy storage capabilities. This research aims to combine the load-bearing capabilities of existing battery materials to build mechanically robust cells, resulting in significant packing volume and weight reductions.^{2,41} Recently some MESCs were developed by different researchers, capable of fulfilling the ongoing

demand for multifunctional composites for structural applications.^{33,42–46} However, the use of thermoplastic materials for power integration, cell performance deterioration under loading conditions, and compromised mechanical properties are the significant challenges that hinder the widespread use of MESCs. Here, our proposed MESCs are made using an integrated approach that involves embedding Li-ion battery electrode materials in high-strength CFRP composites. To reduce the risk of conventional Li-ion battery, a modified version of Li-ion battery, lithium-polymer (Li-Po) was used in this work. Due to the sandwich-style construction, the laminate's moment of inertia increases significantly, resulting in increased flexural rigidity.^{40,47,48} There is no need to modify the electrochemistry of Li-ion batteries in this approach, and it can be adapted into conventional industry designs, which are critical for engineering implementation. Finally, the MESCs made of electrospun CNT/epoxy nanofibers enhanced CFRP laminates can bear three times higher load than the standard MESCs fabricated with regular laminated CFRP.

2 | METHODOLOGY AND CHARACTERIZATION

2.1 | Solution preparation for air-spraying and electrospinning

In this study, a masterbatch of nonfunctionalized MWCNTs which is comprised of epoxy resin based upon Bisphenol A (50–99 pbw. %), ethanol solvent (<15% volume), and multiwalled carbon nanotubes (10W) (Nanocyl™ S.A., Belgium) were used. The masterbatch was diluted with neat epoxy (Miller-Stephenson) in the presence of dimethylformamide (DMF) and Triton X-100 through rigorous magnetic stirring to produce 4W CNT/Epoxy (w/w) solution. DMF and Triton-X used in the experiments have been provided by Sigma-Aldrich, unless it is noted. CNT (4W) with epoxy (w/w) was optimized in our previous studies.^{49,50} To acquire a uniform and well-dispersed CNT polymer solution, high power probe sonication was used in continuous time periods (40 s on, 30 s off for 2 h). Next, a curing agent was added to the mixture (20:1 w/w) with a resting time of 20 h to make a semicured solution with the viscosity 65p necessary for the electrospinning method. The solution was degassed in a vacuum furnace to remove any air-bubbles in the last step. Syringes used for electrospinning were loaded with the final nanocomposite masterbatch mixture, and electrospinning was executed on one side of the prepreg. The electrospinning method was optimized at a high voltage of 16 kV with the needle gauge and feeding

rate of 23 G and 0.25 mL/h, respectively. A metallic collector was located 10 cm from the tip of the needle. The masterbatch was extruded from the needle tip and deposited on a composite prepreg layer fitted on the stainless-steel collector, resulting in a CNT/epoxy nanofiber scaffold as demonstrated in Figure 1A. The process of fabricating submicron CNT/epoxy filaments is shown in Figure 1B. Similarly, CNT/epoxy solution was loaded in a high-volume low pressure (HVLP) spray gun and sprayed on the prepreg layer with a specific air pressure (1.01 bar) to serve as a control.

2.2 | Electrospun and airsprayed CFRP face sheets sample preparation

An MESC cell is made up of essential components. This study's design and analysis of the cell sample is a material optimization problem. The face sheets' material selection and geometric configuration allow for a wide range of possible combinations of electromechanical properties. At the same time, remaining consistent with the load-carrying performance of the material in terms of distortion susceptibility under a three-point bending load is necessary. Electrospinning and air spraying of CNT/epoxy were used on 16 layers of plain weave prepreg measuring 10 cm × 10 cm (SE70 Gurit Holding AG, Wattwil, Switzerland). A hand layup

approach is used in reducing the void ratio, followed by vacuum bagging. The stacking sequence on both sides of the cell is $[0/90/\pm 45]_{2s}$, as shown in Figure 1C. Square slots were cut from two layers on each side before stacking. Before curing, the samples were vacuum bagged for 60 min to ensure optimal adhesion between the layers. The samples were thoroughly cured by placing them in a programmed oven (OV301 Precision Composites Curing Oven, Easy Composite, UK) for 25 min at 120° C and vacuuming under 1 bar. The samples were cooled to room temperature while the pressure was kept constant. For esthetic purposes, the edges of the samples were smoothed using sandpaper. After the curing procedure, the sample's ultimate thickness was 0.52 cm. Similarly, two additional CFRP face sheets with eight layers of pristine prepreps were made for comparison (no electrospinning or air spraying of CNT/epoxy).

2.3 | Assembly of the batteries inside the CFRP samples

The fabrication method of the MESC cell was operated sequentially, as shown in Figure 2A. Two CFRP face sheets with the rectangular slot (60 mm × 40-mm × 0.5 mm) in the middle are placed flat on the surface. A 0.8 mm, thick Li-Po battery (Capacity: 50 mAh,

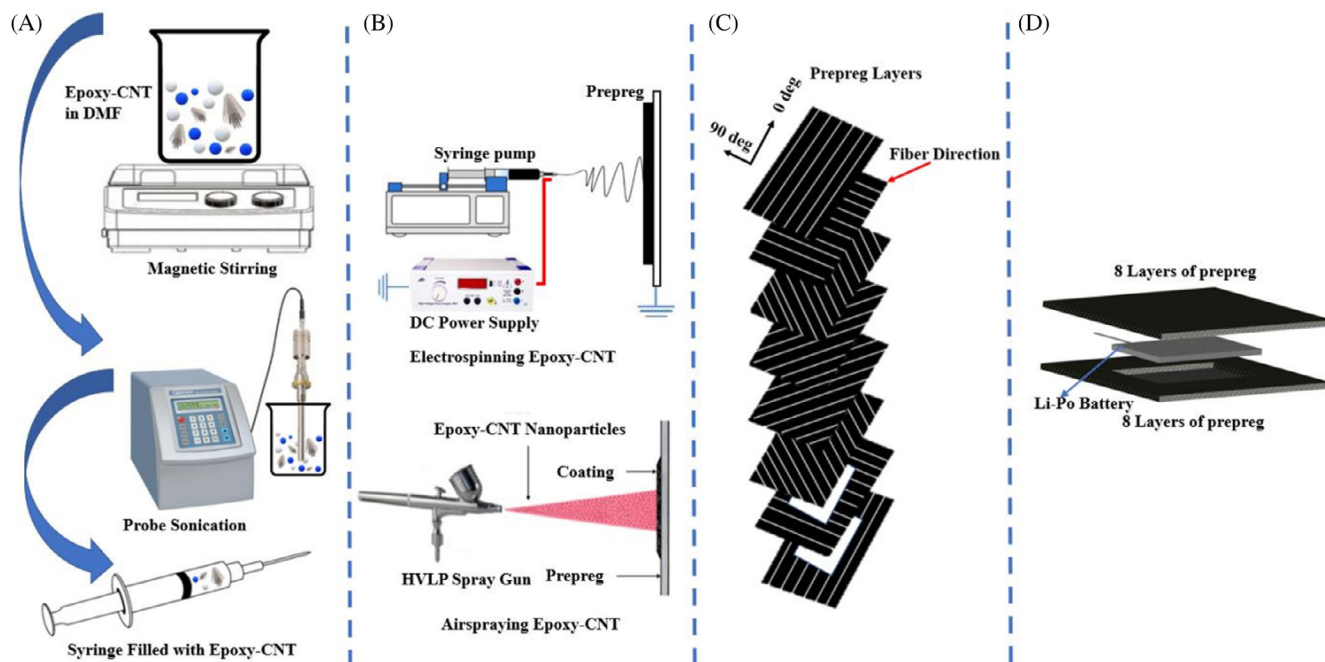


FIGURE 1 Schematic illustration of electrospinning and air-spraying of CNT/epoxy: (A) CNT/epoxy solution preparation, (B) electrospinning and air-spraying, (C) stacking the prepreg layer $(0^\circ/90^\circ/\pm 45^\circ)_{2s}$, and (D) integration of Li-ion battery in the core of the structure

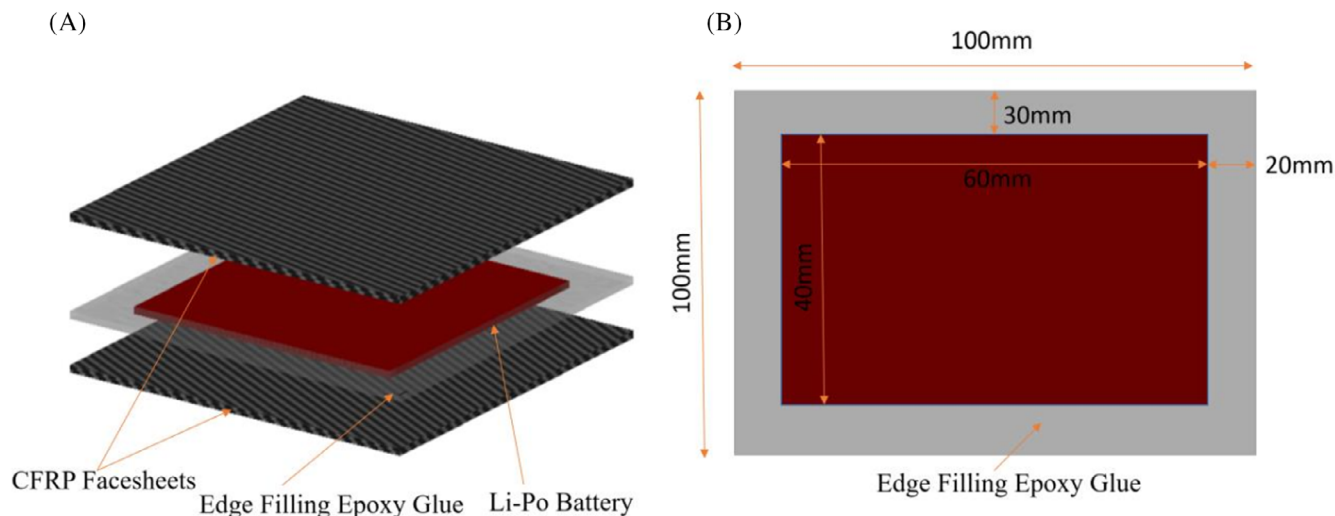


FIGURE 2 (A) Multifunctional energy storage composite assembly and internal components, and (B) dimensions of the composite structure and Li-Po battery

GM0086535 50mAh, Powerstream) with the same length and width as the slot was placed on the slot of one face sheet. The rest of the surface was coated with premixed epoxy glue (pristine bisphenol-A epoxy with a hardener in a ratio of 20:1), and a sandwich structure was built. The sample is then compressed in a heated hydraulic press to further melt the epoxy resin in the middle section of the sample and fuse the surfaces of the face sheets securely (100 °C, 0.5 MPa pressure). The sample was cooled at room temperature under the same pressure; during this phase, the epoxy glue cured and thus equilibrated the stack mechanically. Edges of the sample were then sealed off with additional epoxy adhesive to homogenize the two surfaces. This method was applied to produce three different samples (electrospun face sheet, air sprayed face sheet, and conventional face sheet). The second type of sample assembly involves the application of thermoplastic at the center of the two surfaces instead of the uncured epoxy glue.⁴⁰ The thermoplastic sheet was made of polyethylene-co-acrylic-acid (EAA) ionomer with 1.5 mm thickness. The final sheet was then cut according to the shape of the CFRP face sheet with an empty square slot in the middle for accommodating the battery. Then the structure was assembled with a hot press (100 °C, 1 MPa pressure). Due to the high temperature on the edges of the thermoplastic sheet, it is in a melted state, acting as the adhesive for the other side of the CFRP face sheet. As in previous work, the MESC was manufactured with the help of thermoplastic materials, which have severe thermal instability. This type of MESC was analyzed as a control in this study, only to compare with the proposed ones.

2.4 | Characterization

Field emission scanning electron microscope (FESEM, JEOL 7800f, Japan) images indicated that MWCNT is homogeneously integrated inside the epoxy solution and no significant change in the epoxy shape was seen. The even distribution maintains the characteristics of epoxy, at the same time, enhancing its mechanical properties. This uniform dispersion of nanotubes is achieved because of DMF (a polar solvent) and then adding plasticizers to avoid the formation of clusters. Figure 3A reveals SEM image of the CNT/epoxy nanofibers after electrospinning. The average fiber diameter was 147 nm with a relative standard deviation of 10 nm averaged across 10 different samples. Figure 3B shows the airsprayed CNT/epoxy on the carbon fiber which was not as uniform as the electrospun nanofibers. The air sprayed spherical shaped CNT/epoxy on carbon fiber was measured to 1–1.5 μm , and fibers connecting those were measured to be 300–400 nm.

3 | RESULTS AND DISCUSSION

3.1 | Mechanical properties

3.1.1 | Quasi-static three-point bending test

The interlaminar shear strength (ILSS) test sampling method is more appealing than the other shear tests. Figure 4A shows the load–displacement curves, and the corresponding ILSS values for each fabricated laminate configuration, that is, air sprayed CFRP, control CFRP,

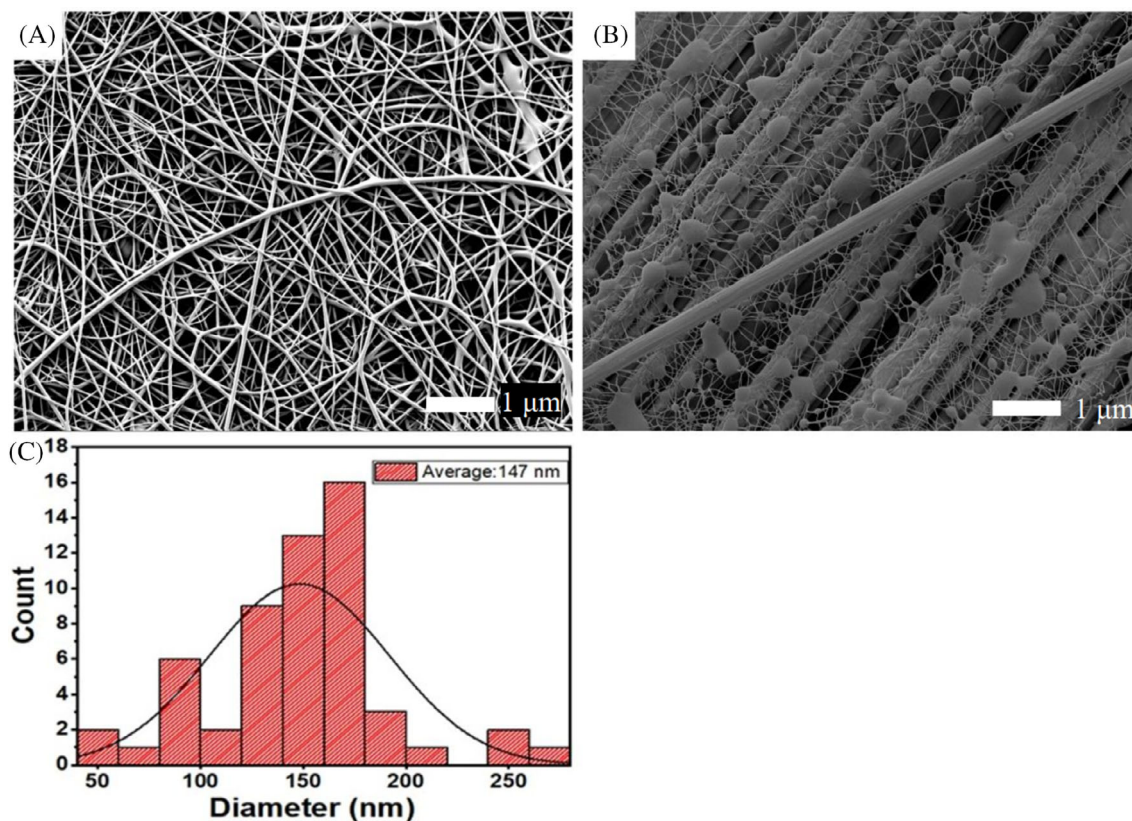


FIGURE 3 SEM images of epoxy-MWCNT coated on CFRP sheets, (A) electrospun epoxy-MWCNT nanofibers, (B) Airsprayed epoxy-MWCNT on CFRP sheets, (C) size distribution of electrospun epoxy-MWCNT nanofibres

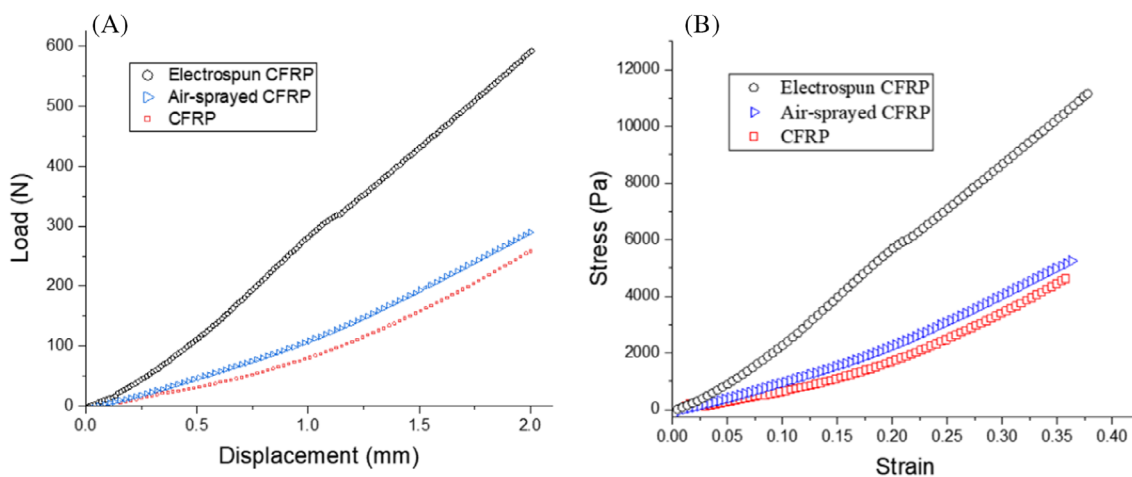


FIGURE 4 (A) Load versus displacement curves for different CFRP structures with Li-Po battery, (B) strain vs stress curves for different CFRP structures with Li-Po battery

and electrospun CFRP-based MESC. Figure 4A shows that the displacement increased in the elastic liner region to reach the peak load. The electrospun sample with the 4 wt.% CNT/epoxy produced the highest peak load with 595 N. To keep an ideal state in which the battery can withstand the most load without compromising its electrochemical properties. We kept the displacement limit to

2 mm. It was also discovered that the laminate layers at the top did not bend and that the maximum load could be increased further because there were no displacement constraints.

On the other hand, the traditional CFRP specimen exhibits the lowest peak load of 259 N and subsequent deformation in its upper layers. Compared to the

traditional CFRP sample, the air sprayed CFRP sample had a peak load of 289 N and less substantial damage in the upper layers. Before entirely deforming, the pouch cell battery itself could not withstand a peak load of more than 6 N. Figure 4B shows the strain and stress graphs with an overview of the flexural strain and stress and bending elasticity. For the same level of strain, electrospun CFRP based MESC showed three times higher stress than the regular and airsprayed CFRP-based MESC. The experimental finding is responsive to the testing procedure based on the specimen, loading shape, and strain rate. This test determines the maximum shear stress necessary to fracture the samples, and the stress–deflection curve slope is calculated. In the support, the bending moment is zero, and at the center, it is maximum.

For the characterization of the three laminate samples, two types of orientations were used, asymmetric and symmetric. A symmetric structure is where eight layers of prepreg were placed on both sides and Li-Po battery was in the center of structure as shown in Figures 1D and 2A. An asymmetric orientation was used in the top with 12 layers of CFRP, and four layers were used in the bottom of the battery, as shown in Figure 5A. Altogether, there were 16 layers of the CFRP on the battery packaging for both symmetric and asymmetric orientation. Moreover, both top and bottom cured layers were combined as a sandwich with epoxy glue, as shown in Figures 2A and 4A. During the bending test, compression load was applied on the thicker side of the asymmetric MESC. For 2 mm displacement, it was observed that asymmetric MESC could bear a slightly higher load than the symmetric ones (Figure 5B). There is a hollow structure in the center in symmetric MESC whereas it is far from the center in asymmetric ones. Therefore,

asymmetric MESC could withstand more load than symmetric ones.

A comparison was carried out between the electrospun CFRP having epoxy glue in the core and the electrospun CFRP with a thermoplastic sheet at its core to act as a packaging method for the pouch cell battery. Table 1 represents the two-sample specimen's dimension, thickness, and weight, and the load and displacement curves are represented in Figure 6A. The addition of the thermoplastic layer decreases the load capacity of the MESC compared to the electrospun CFRP with epoxy glue. This is due to incorporating the thermoplastic layer in the center, which reduces the interlaminar shear strength of the MESC structure and helps delaminate two CFRP laminates easily. The electrospun CFRP-based MESC with epoxy glue achieved a better shear stress transfer through the electrode stack of the pouch cell to the CFRP layer and reduced the thickness by 55%. Also, it was observed that due to the transverse shear stress and the slipping motion of the pouch cell with the CFRP layers, the MESC has higher bending stress, increased load capacity, and reduced displacement. Load and displacement curves were obtained without the pouch cell for the electrospun CFRP and conventional CFRP-based MESC structures to understand the failure criteria. The tests were conducted without any constraints on the displacement criteria. The conventional CFRP structure could withstand a peak load of 1500 N with no deformation, while the electrospun CFRP structure withstood up to 2000 N, as shown in Figure 6B. For the bending test, Test Resources (Model 240–750, 200 series, 2 kN) were used, so it could be predicted that the electrospun CFRP could withstand more than 2 kN.

We observed no resistivity against the mechanical deformation on the pouch cell battery control and

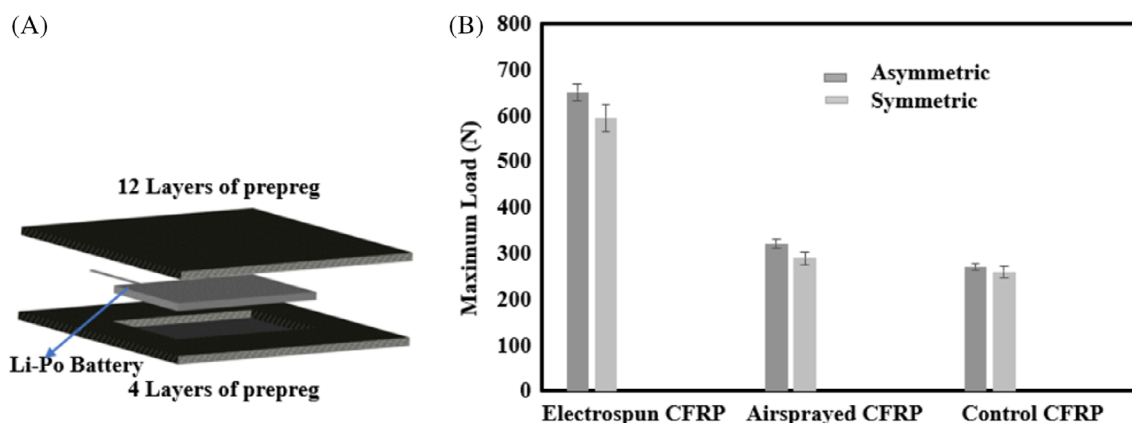


FIGURE 5 (A) Schematic of asymmetric MESC formation, (B) for 2 mm displacement, the maximum load bearing capacity of symmetric and asymmetric CFRP based MESC structures

TABLE 1 A comparison between electrospun MESC with epoxy glue and thermoplastic sheet in the center of the composite structure

Sample type	Electrospun MESC with epoxy glue	Electrospun MESC with a thermoplastic layer	Pouch cell integrated inside
Sample Dimensions (L × W) (mm)	(100 × 100)	(100 × 100)	(60 × 40)
Sample thickness (mm)	5.30	11.58	1.2
Sample weight (g)	63.54	84.35	05

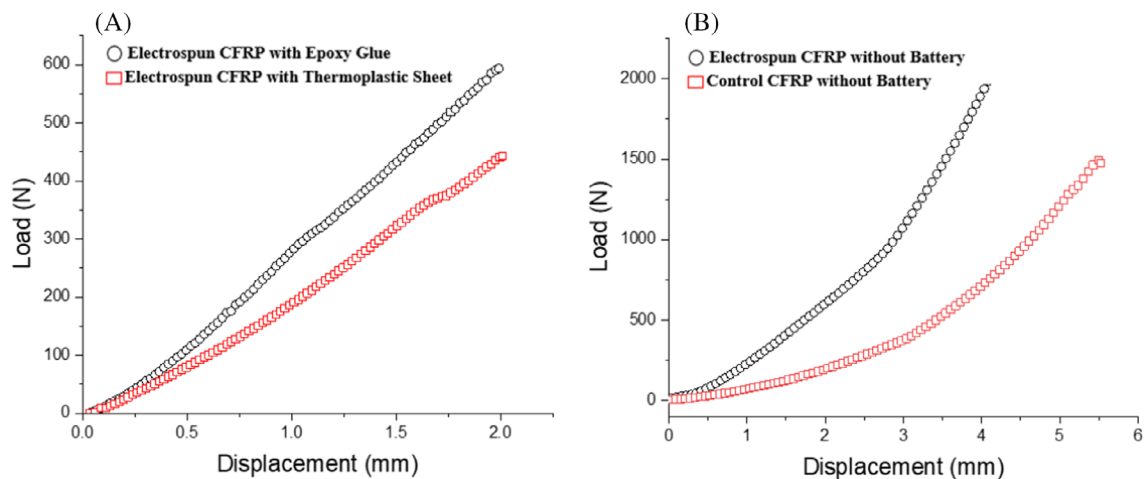


FIGURE 6 (A) Load vs. displacement curves for comparison between electrospun CFRP cell and electrospun thermoplastic CFRP cell, (B) load vs. displacement curves for CFRP structure without batteries

showed an extreme nonlinear behavior with a permanent deformation after unloading. It is mainly due to the inability to return after the loading deformation with no elastic mechanical constraints. However, we saw improved elastic mechanical constraints on MESC samples with a liner behavior until they reached their maximum load capacity. MESC samples could withstand a continuous changing of their loads with a minor deformation of their structure, making them ideal for many applications due to their improved response against mechanical fatigue.

3.1.2 | Flexural rigidity

Flexural testing is the most practical approach for evaluating improvements in interlaminar characteristics at the fiber-resin interface. The electrospun CFRP sample showed the farthest flexural strength and modulus compared to the control CFRP samples, as shown in Figure 7. The CNT/Epoxy electrospun-enhanced CFRP specimen was considered due to prior research experiments conducted by our group,^{49,50} demonstrating that incorporating of nanofiber reinforcement mats increases flexural properties. The Li-Po battery packaging in electrospun

CFRP and control CFRP-based MESC showed flexural strength of 10 and 80 MPa, respectively, which is more than 33% increment. Similarly, electrospun CFRP and control CFRP-based MESC showed flexural modulus of 8.39 and 4.19 Ga, respectively.

3.2 | Electrochemical performance

Landt battery analyzers (Landt Instruments) were used to cycle the batteries. The temperature was kept constant

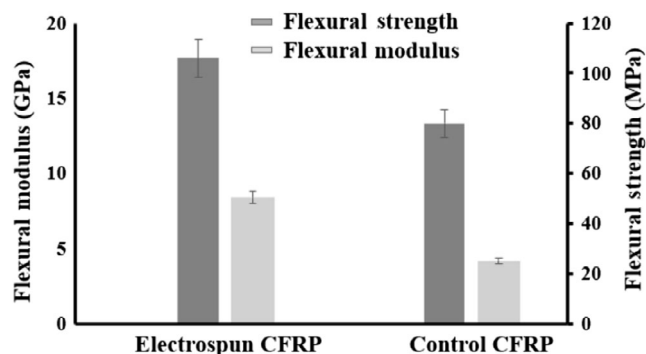


FIGURE 7 Flexural strength and flexural modulus of electrospun CFRP and control CFRP based MESC

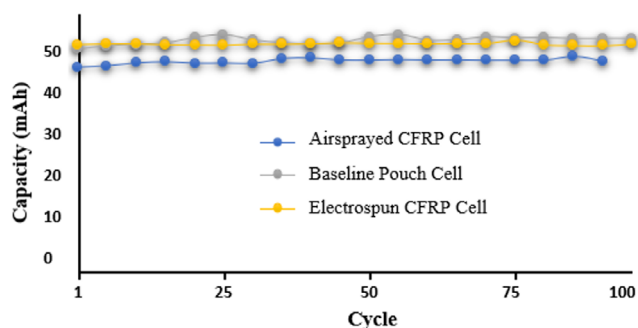


FIGURE 8 Capacity versus cycle numbers of different MSEC under loading conditions at 0.5C rate and regular pouch cell without any load at 0.5C

at 30 °C for all the electrochemical testing. The conventional pouch cell battery was subjected to cycle testing before the bending test and after to observe the electrochemical behavior. The battery failures were caused by the CFRP cells with air-sprayed and conventional samples spread over the entire load-carrying portion of the laminate samples, causing deformation in the batteries. The load applied in the central section of the structure causes this deformation, but the battery does not fail under bending load because the composites' ultimate failure strain is greater than the pouch cell battery. The voltage (charge or discharge at 0.5C and 1C rate, respectively) cycles, as well as the capacity values of the battery, have been recorded. Normally, the pouch cell and other cells integrated inside electrospun, airsprayed and control CFRP laminates perform exactly the same. It indicates that the pouch cell battery and the electrospun CFRP cell under loading condition display the same electrochemical characteristics in cell capacity as shown in Figure 8. Battery capacity of airsprayed and control CFRP cell deteriorated gradually. Similarly, as shown in Figure 9, the voltage profile of Electrospun CFRP cell after 40th cycle looks as same as the 1st cycle whereas

the airsprayed and control CFRP show degradation in performance. This demonstrates that, in terms of testing properties, CNT/Epoxy electrospun CFRP-enhanced cells are the best approach for MESC.

The embedding of Li-Po batteries in different configurations within the sandwich CFRP surfaces core presents a novel approach to structurally embedding batteries in a distinctive material with a vertical integration method. Under the design of MESC, the fundamental mechanical properties of CFRP materials enable the industrial-standard Li-ion battery to be far more resilient in structural applications. These improvements do not affect the fundamental chemistry or functionality. The bending stiffness of the structure has no bearing on the presence of the batteries within the sandwich composite. Also, when the probability of a failure was limited to the metal gouge on the structure's core, the highest strength in electrospun CFRP sandwich constructions did not influence the batteries. There are three types of CFRP face sheets used in the MESC structure: conventional CFRP, air sprayed CFRP, and electrospun CFRP. When there is no packaging in the external media, the unique characteristic of each structure enables better interlayer shear movement and attaches the electrodes of the battery securely to stabilize the loose electrodes that endure bending loads. This allows the mechanical loads to be carried by the layers of electrospun and air-sprayed samples. Even though the samples were subjected to the possibility of severe failure under deformation by indentation, the electrochemical characteristics of batteries, such as internal resistance, charge/discharge properties, and capacity, were not changed throughout the bending and tensile loading (Figure 9). The incorporation of Li-Po batteries resulted in a significant increase in the mass of the sandwich composite, as they are significantly denser and can enhance the structure's self-weight while simultaneously lowering its strength and stiffness. The design might support specific properties to increase

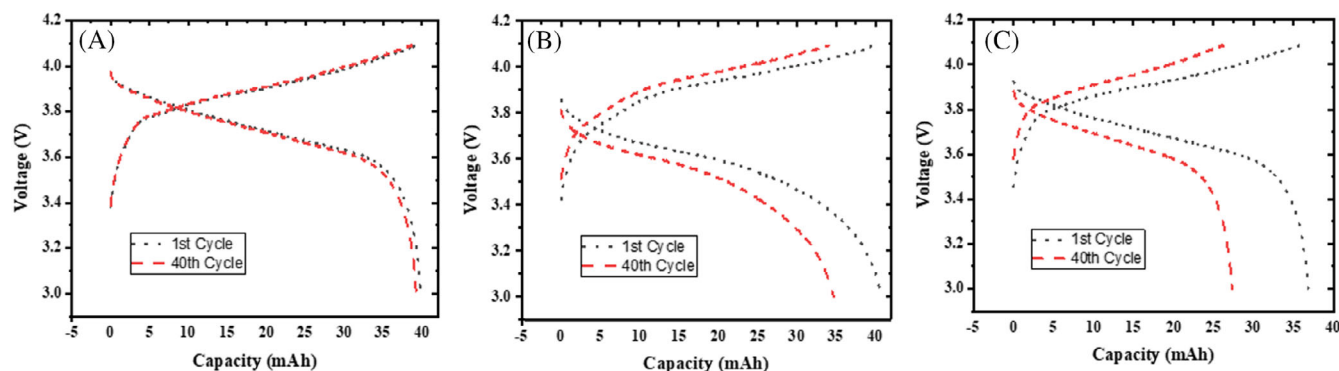


FIGURE 9 1st and 40th cycle charge-discharge curves at 1C rate. (A) Electrospun CFRP cell under loading condition (595 N), (B) Airsprayed CFRP cell under loading condition (289 N), and (C) control CFRP cell under loading condition (259 N)

energy storage density to achieve lightweight constructions in this situation. The electrospun CFRP samples, which were lower in weight and thinner in construction than the air-sprayed and traditional samples, resulted in maximum mechanical strength with intact electrochemical performance.

4 | CONCLUSIONS

This work successfully demonstrated a novel form of energy storage integration in the core of a composite structure without compromising the mechanical and electrochemical properties. In contrast to recent other research, the absence of thermoplastic materials results in a thermally and structurally stable construction. Electrospinning of CNT/epoxy nanofilaments in-between CFRP layers helps produce high-strength CFRP laminates, which prevent the interlayer shear movement of the battery electrodes by carrying a much higher load. For 2 mm displacement, electrospun CNT/epoxy-enhanced MESC can withstand more than three times higher load when compared to conventional CFRP-based MESC structures. The Li-Po battery between the two electrospun CNT/epoxy-enhanced CFRP facesheets attached by epoxy glue performs 50% better than the thermoplastic adhesive materials.

Similarly, epoxy glue shows more than two times higher load carrying capacity than thermoplastic adhesive without the battery inside. In this process, interfacial toughening of CFRP materials by electrospun CNT/epoxy nanofilaments makes the industry standard Li-Po battery much more robust for structural applications. Integration of the battery in the core of MESC does not affect on the basic battery chemistry, and the battery's functioning is identical to that of a pouch cell battery under no load condition. The electrochemical properties of batteries like the internal resistance, charge/discharge properties, and capacity were not distorted during the bending and compression loads even if the samples were exposed to a possibility of severe failure under deformation by indentation. In this work, energy storage with moderate energy density was used to show that by increasing the mechanical and physical properties of CFRP facesheets through electrospun nanofilaments, new generation MESC can be produced with better safety and environmentally friendly features.

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