



Multifunctional carbon fibre reinforced polymer (CFRP) composites for sustainable and smart civil infrastructure: A comprehensive review

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ABSTRACT

Carbon fibre reinforced polymer (CFRP) composites have gained extensive use in aerospace, transportation, and civil infrastructure due to their superior mechanical performance, chemical resistance, and lightweight characteristics. Recent advances have shifted focus toward enhancing their electrical and functional properties to enable smart capabilities. This review provides a comprehensive overview of the latest progress in raw materials, factors influencing electrical conductivity, and multifunctional properties of CFRP, including self-sensing, electromagnetic interference (EMI) shielding, self-heating, energy harvesting, and storage. Self-sensing in CFRP, driven by its piezoresistive behavior, enables detection of compressive, tensile, flexural, impact, and fatigue loads. Remarkably, CFRP can also be engineered to serve as massless structural energy harvesters for electrical power generation or as supercapacitors for electrochemical energy storage. Despite these advances, challenges remain in large-scale production, thermal stability, long-term durability, and wireless signal acquisition. From this perspective, mineral-based CFRP composites (MCF) might offer a promising pathway to address these issues. This review aims to inform future research directions and support the development of multifunctional and sustainable CFRP composites for smart infrastructure applications.

1. Introduction

The combination of carbon fibre (CF) with polymer matrix provides composites with high strength, high resistance to chemical attacks, low density, and excellent mechanical properties. Continuous carbon fibre reinforced polymer composites (CFRP) have been widely applied in different industrial sectors as high-strength and low-density lightweight components, ranging from aerospace, transportation, wind power generation to civil engineering concrete structures [1]. Previous studies utilized the electrical resistivity of CFRP for the breakage detection of CF [2]. In addition to the mechanical and durable superiorities, increasing studies are attempting to explore the multifunctional properties of CFRP such as the piezoresistivity, electromagnetic interference (EMI) shielding, Joule or Ohmic heating, energy harvesting and storage, etc. As shown in Fig. 1, the multifunctionality of CFRP enables it to be one of the smart components or elements in some key structures, such as the deicing pavement, EMI shielding shell, damage self-monitoring concrete

structures or even future a rechargeable battery.

Many studies have attempted to evaluate the electrical and piezoresistive properties of short carbon fibres filled cementitious and polymeric composites due to the excellent electrical conductivity of carbon fibres. They demonstrated the potential stress and strain self-sensing performance of the short carbon fibre reinforced composites for structural health monitoring based on the electrical resistivity changes [3–8]. Similarly, the electrical resistivity of CFRP can be captured from the breakage or detachment of continuous carbon fibres when the composites are subjected to multiple loading conditions. During electrical signal data acquisition, it should be noted that the electrodes and their ohmic contact to the CFRP are critical to the accuracy and stabilization of piezoresistivity. The poor connection between electrodes and composites may induce negative piezoresistivity of CFRP under tensile loading [9]. Lee et al. [10] investigated the electrical resistance changes of CFRP subjected to drop impact based on the probabilistic sensing cloud method and optimized the placement of electrode to achieve the

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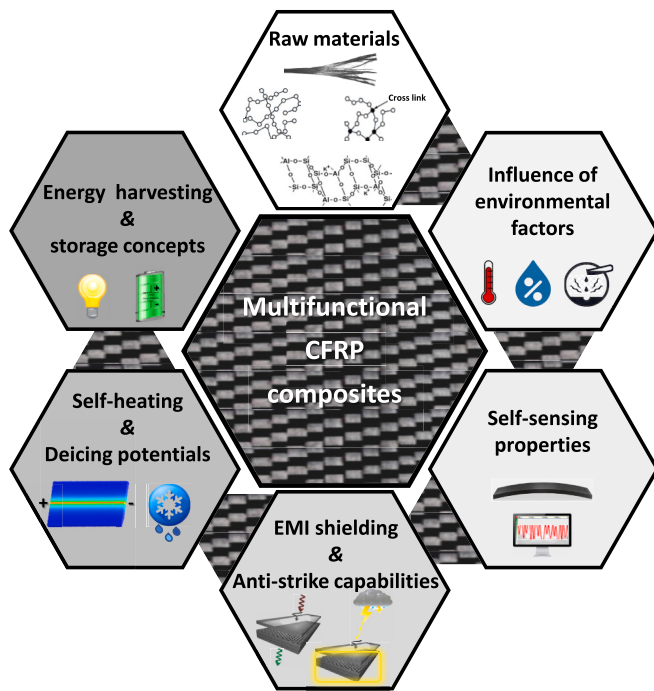


Fig. 1. Potential applications of multifunctional CFRP composites.

best sensitivity. The improved piezoresistivity-based monitoring system possessed lower noise, fewer electrodes, and error components. In addition, to prevent contact resistance, four-electrode method rather than two-electrode method is usually applied for the electrical resistance measurement.

Electromagnetic interference (EMI) shielding becomes more important with the development and wide application of electrical devices and telecommunication technology in daily life. It has been proposed that the composites with excellent electrical conductivity are more likely to reflect electromagnetic waves, while the counterparts with high magnetic permeability tend to absorb the electromagnetic waves [11,12]. CFRP composites have been widely applied to substitute metallic materials for EMI shielding, due to their lower cost, higher corrosion resistance, excellent electrical conductivity, and mechanical properties. To improve the shielding effectiveness (SE) of CFRP, many investigations have figured out various solutions ranging from additional coatings, mixed nanomaterials, metallic powders to carbon fibre activation. Zhu et al. [13] developed a nylon filter/nickel sandwiched film by chemically depositing on the CFRP and obtained high SE (63.1 dB) under the frequency of 8.2–12.4 GHz. By dry spray deposition of carbon nanotube (CNT) on the interlaminar surfaces of carbon fibre prepreps, Gong et al. [14] produced the CNT filled CFRP without additional CNT dispersion. The treatment improved the maximum and minimum SE of modified CFRP by 20 % with only 2.5 g/m² CNT added to the surface. It is different that Jang et al. [15] dispersed the ion powders with an epoxy matrix before impregnating the carbon fibres. The uniform dispersion of powders in epoxy should be solved in this study, but the improved SE still reached more than 50 dB. Interestingly, as individual wefts and warps, the CFRP yarns could be woven with nickel wire mesh yarns to produce a metal-carbon textile composite for the enhancement of EMI shielding [16]. This technique develops hybrid metallic carbonic CFRP - a straightforward way without additional coating, deposition, and dispersion processes.

Self-heating of CFRP provides a new option for automatic pavement deicing compared to the traditional method of salting and manual cleaning. Mohammed et al. [17] found that both the carbon fabrics and carbon fibre yarns were capable of heating the concrete slab when they were embedded into the concrete specimens, and the carbon fibres yarns

performed better than those in the form of woven or unidirectional fabrics. They also proposed that the moisture inside concrete would not significantly reduce the heating performance. Mechanical degradation of concrete slab with embedded carbon fibres products was not mentioned. Maleki [18] observed the firstly increased and then decreased compressive strength of concrete with increasing content of chopped CFRP. Meanwhile, the heating time was continually decreased with the increasing conductive filler. It indicates that the content of CFRP should be controlled to a certain optimal value, to maximize the heating efficiency and maintain the mechanical properties. To improve the heating efficiency and save electricity, Cao et al. [19] developed the Ni-coated CFRP, and found that the electro-thermal conversion rate improved by 32.5 % compared to the plain CFRP. The carbon fibre cloth had been cooperated with heat transfer and insulation layers to establish the self-heating sandwich structure, which further improved the heating and deicing efficiency when embedded into the concrete [20].

The multifunctional properties of CFRP also include the energy storage capacity when the composites work as a supercapacitor. All those functions have great potential to be applied in civil engineering construction. Some studies involving the short CF reinforced polymer composites for multifunctional applications are also briefly summarized. Considering the majority of studies on CFRP are focusing on the mechanical and durable properties [21], this review paper is mainly attempting to summarize the raw materials of CFRP production, the environmental factors that influence the functions and the multifunctionality, thus improving the understanding and practical technology/functionality transfer on the new generation of commercial multifunctional CFRP. To better guide future research and practical adoption, the key challenges and research gaps of multifunctional CFRPs are summarized in Section 8.

2. Raw materials

2.1. Carbon fibre

2.1.1. Precursor

The precursors are critical for the ultimate properties of the resultant CFs and the most common industrially used for CFs production are polyacrylonitrile (PAN), mesophase pitch (MP) and cellulose-based (e. g., rayon and lignin), as illustrated in Fig. 2a. Thus, according to the precursor selection CFs production varies and requires different conversion processes [22]. An ideal precursor material should be efficiently and cost-effectively converted to CFs with a high carbon yield after the carbonization procedure step. PAN-based CFs exhibit a 68 % carbon content with a carbon yield of 50–55 % after carbonization, whereas cellulosic-based CFs exhibit a carbon content of 44.4 % with a carbon yield of only 25–30 %. MP-based CFs present a higher carbon content and a higher yield of 85 %, but also combined with poorer compression and transverse properties compared to the PAN-based [23]. Generally, PAN-based CFs are characterized by lower density, higher strength and reduced production costs compared to their counterparts. On the other hand, MP-based CFs are identified by higher electrical and thermal conductivity values and a higher Young modulus [24]. Nowadays, almost 96 % of the global CFs production relies on the PAN precursor. However, after more than 50 years of research and development on PAN-based CFs their achieved mechanical properties are far from the theoretical values. Indicatively, CF filaments are 10 % of the theoretical strength due to carbon-carbon bond and the Young modulus is around 30 % less than the principle [23]. Consequently, extended investigations are needed to reach both properties to a superior level at the same time. CFs application areas are stimulated by their attractive properties, such as strength to weight ratio, electrical conductivity, chemical stability, low-to-negative resistance to shock heating, thermal expansion coefficient. With regard to sustainable and renewable precursor resources, recently lignin-based CFs have gained more and more research attention [25].

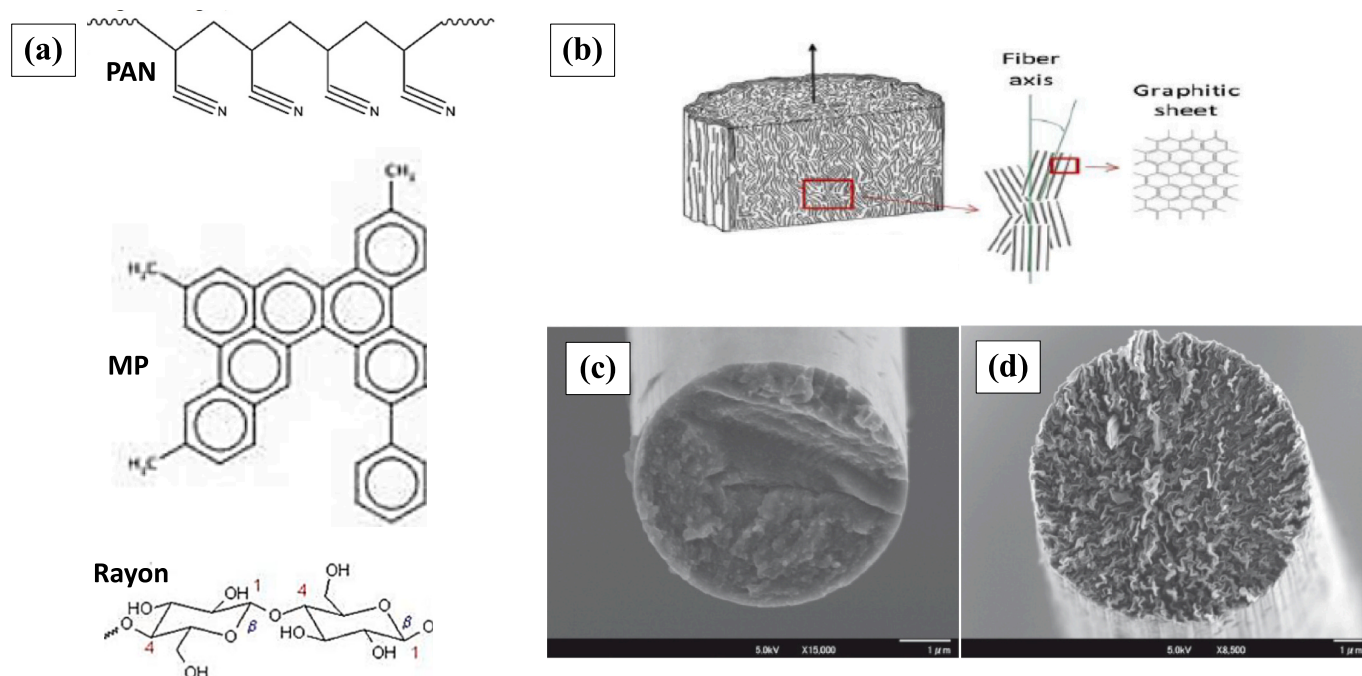


Fig. 2. (a) Chemical structures of the most commonly used PAN precursors for CFs production, (b) schematic representation of the cross-section CFs microstructure and (c, d) scanning electron microscopy imaging for PAN and pitch-based CFs, respectively. [24]

2.1.2. Microstructure

Optimizing the CFs microstructure in Fig. 2b can improve CFs strength through decreasing its flaw sensitivity. Tailoring crystal structure features and porosity of the CFs implies a great variety of different grades with unique mechanical and electronic properties, which strongly depend on the production procedures and the further processing parameters [26]. CFs may be turbostratic or graphitic or present a hybrid microstructure with both graphitic and turbostratic parts [24]. PAN-based CFs tend to be turbostratic (see Fig. 2c), whereas CFs derived from MP become graphitic (see Fig. 2d) after a heat treatment at 2200 °C. Turbostratic CFs are correlated with high tensile strength and the more graphitic CFs are correlated with high Young's modulus. Technically, the final morphology is determined by the carbonization and the optional graphitization degree. The reactions occurred during carbonization are rather complex and difficult to monitor by analytical methods. In principle, the depolymerized amorphous char, which is formed during pyrolysis, is rearranged, and condensed to form polycyclic rings, aromatic structures and graphite-like layers. As a result, microcrystallites are formed consisting of sp^2 and sp^3 hybridized carbon atoms. Typically, carbonization is carried out under an inert atmosphere in temperatures up to 1500 °C and is accompanied by fibre shrinkage and density increase [27]. As proof, the commercially successful T700 PAN-based CFs presented an orientation degree of the graphitic basal planes gradually decreased from the skin region to the core one, after thermal treatment at 1000 °C. By gradually increasing the thermal treatment process, the graphitic basal planes are arranged parallel to the CFs axis, initially in the skin and afterwards in the core region. At the same time, the size of the crystallites increases faster in the longitudinal direction, resulting in nanometer-scale pores formation upon the crystallite size increase [28]. Graphitization takes place at temperatures between 1500 and 3000 °C and leads to a carbon content of more than 99 % with a growth of the graphitic layers. Furthermore, graphitization under tension yields superior mechanical properties due to the further improvement of the carbon ribbons anisotropy along the filament axis. Regularly, graphitization is characterized as a power-consuming process increasing the total production costs and the field of applications is mainly limited to demanding aerospace structures reinforcement [29].

2.1.3. Mechanical properties

The tensile modulus and strength of CFs are directly related to the internal and external flaws of the grown crystal size, the specific skin microstructure features and the core orientation within the CFs [28]. For instance, MP-based CFs possess the highest density of 1.9–2.2 g/cm³, while cellulose-based CFs possess the lowest of 1.66 g/cm³ with a highest elongation at brake of 1.6–1.8 % [30]. The maximum temperature in air at which the mechanical properties remain unaffected is 300 °C. Fig. 3a summarizes the tensile modulus versus tensile strength for commercially available PAN and MP-based CFs. Typically, CFs are classified regarding their nominal manufacturer's reported tensile modulus and strength values as CFs for general purpose (GP), for high strength (HS), for intermediate modulus (IM) and for high modulus (HM) [23]. More specifically, low-cost, and low crystalline orientation GP CFs are used for light reinforcement and conductive applications with a tensile modulus in the range of 30–60 GPa and strength of 0.7–1 GPa. Basic HS reinforcing CFs with indicative characteristics of a tensile modulus around 140–240 GPa, strength of 2–3.4 GPa with an elongation at brake 1.1–1.6 % are relatively low-cost and competitive with Kevlar reinforcement. IM CFs (280–350 GPa) with a strength of 5–7 GPa and an elongation at break ca. 2 % often preferred for composites with increased stiffness and compressive strength. Finally, HM PAN-based CFs exhibit the following indicative characteristics of 380–590 GPa (tensile modulus), strength of ca. 3 GPa and elongation at brake 0.5–1.5 % or HM MP-based CFs offer a modulus of 450–965 GPa, a strength of ~3 GPa with an elongation at break 0.2–0.5 % [30].

2.1.4. Electrical conductivity

The electrical properties of CFs are explained in terms of π -electron delocalization and by tunneling or hopping of electrons within a carbon network. Variations in composition and microstructure of CFs is related to production parameters such as possible impurities which can cause changes in electrical resistivity, resulting in purely conducting or semiconducting grades. CFs obtained at lower heat-treatment carbonization processes under oxygen conditions provide mainly p-type semiconducting characteristics [31]. Due to the preferred orientation of the carbon layers along the fibre axis and the anisotropic nature of CFs,

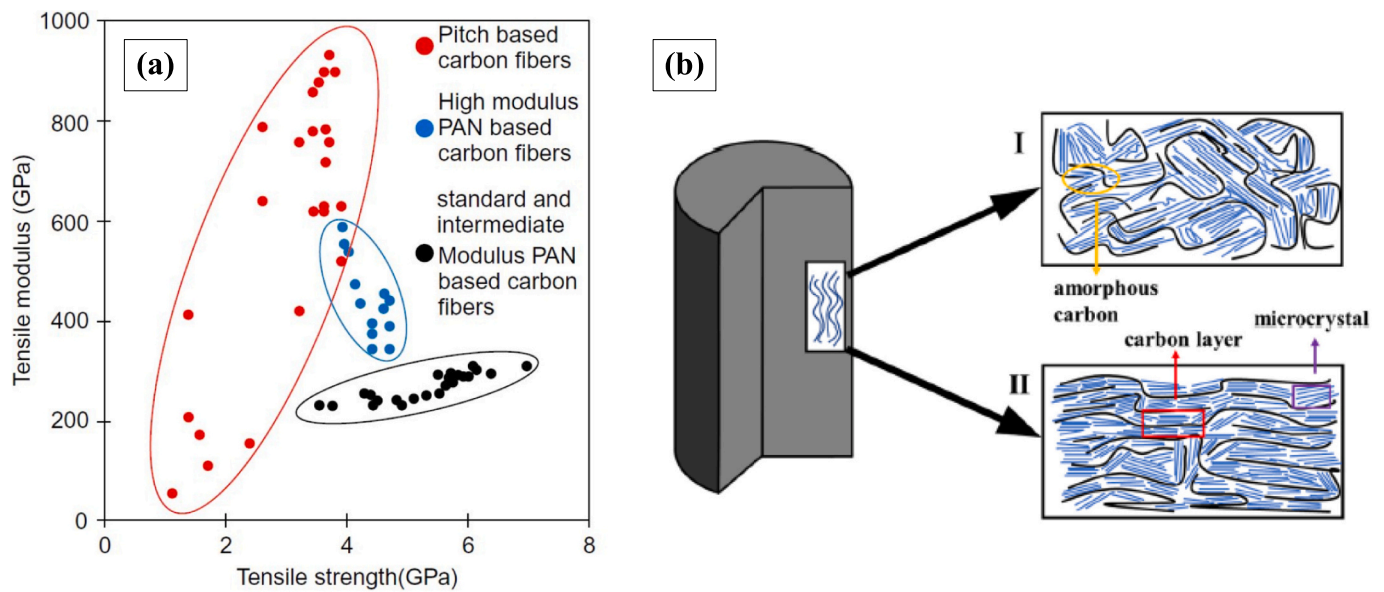


Fig. 3. (a) Tensile modulus-strength graph for various grades of PAN and MP-based CFs. Reproduced with permission [26]; (b) microstructure evolution illustration of the CF filament microcrystals orientation during multiple heat treatment carbonization stages affecting the electrical conductivity values [27].

higher electrical conductivity and elastic modulus values exist in the fibre axis rather than the transverse direction, as schematically shown in Fig. 3b. Piezoresistivity pertains to the conductive nature involving a change in the stored charge on account of an applied strain field. CFs with highly oriented graphene layers present a smaller gauge factor than less oriented CFs. Crystallite reorientation during applied stress combined with the intrinsic anisotropy of electrical conductance in a graphite crystal can significantly influence the electrical resistance [32]. Additionally, the total resistivity is decreasing with increasing density of CFs. This can be attributed to the more aligned microfibrils with a larger available free path for π -electrons transport. Conversely, as the resistivity decreases the tensile modulus and the density increases [27]. Regarding the possible large amount of impurities existing within the microstructure of CFs, both donors (p-type) or acceptors (n-type) charge carriers could impact the semiconducting sign of the Seebeck coefficient value [33]. Subsequently, the generated conductive transport paths possess the ability to allow holes (p-doping) or electrons (n-doping) movement by a plausible tunneling or hopping mechanism [34].

2.2. Polymer matrices

Polymer matrices play a crucial role in determining the overall performance, multifunctionality, and durability of CFRP composites [35]. In this review, the polymer matrices including epoxy resin, polymethyl methacrylate (PMMA), polydimethylsiloxane (PDMS), polylactic acid (PLA), polyetheretherketone (PEEK), and polyamide (PA), were selected based on their widespread application and potential in enabling multifunctional properties. Epoxy resin remains the most commonly used matrix due to its excellent mechanical strength, chemical resistance, and ease of processing, making it ideal for structural applications [36,37]. PMMA and PDMS offer transparency, flexibility, and biocompatibility, which are advantageous for self-sensing and wearable devices. PLA, as a biodegradable thermoplastic, supports the development of environmentally friendly, printable CFRPs with sensing capabilities. PEEK and PA are thermoplastic engineering polymers known for their superior thermal stability, chemical resistance, and suitability in high-performance applications. The following subsections discuss the structure, processing characteristics, and multifunctional performance of these matrices to provide a broad understanding of their advantages and limitations in sustainable civil infrastructure.

2.2.1. Epoxy resin

The composite of carbon fibre reinforced epoxy resin is widely applied in aviation, aerospace and construction structures. In the field of multifunctional research, Crasto et al. [38] proposed that the electrical resistance changes of a single carbon fibre in an epoxy matrix could be used for the evaluation of residual stress in composites, and they investigated the resistance changes with carbon fibre length, temperature, hydrostatic pressure, axial strain and epoxy curing. Wang and Chung [39] firstly proposed the carbon fibre filled epoxy composites as a strain sensor based on the electromechanical effect. However, they only observed the effect in the fibre direction of carbon fibre reinforced epoxy. Considering the piezoresistivity in multidirectional composites with randomly distributed short carbon fibre, this is mainly due to the unidirectional arrangement of the continuous carbon fibres. Also, they observed that the resistance of single carbon fibre could increase by 10 % during epoxy curing at 180 °C and cooling, because of the different thermal contractions between fibre and epoxy [40]. Recently, investigations on the 3D printing of epoxy composites incorporating continuous carbon fibre have gained increasing attention. As shown in Fig. 4, the coated epoxy powders are heated by infrared lighting and then swiftly cooled to produce the carbon fibres reinforced epoxy resin [41]. It provides a new way of considering the industrial production of functional polymer materials with continuous carbon fibres. Although the epoxy is the most widely used polymer matrix with carbon fibre, other thermoplastic matrices are gradually attracting more attention due to some specific superiorities.

2.2.2. Polymethyl methacrylate

Thermoplastic PMMA is a promising candidate to manufacture polymer composites for biomedical applications due to its biocompatibility. To develop the smart PMMA composite as a strain sensor, Kang et al. [42] mixed the dimethyl formamide solvent containing conductive carbon filler with PMMA. The PMMA composite was capable of monitoring the dynamic strain of a cantilever beam when it was attached to the surface. Qu et al. [43] found that the aligned short carbon fibre shifted the percolation threshold of the PMMA composite to a higher value, but the electrical resistivity above the threshold was lower than the composites with randomly distributed carbon fibre. Although some investigations use chopped carbon fibre or carbon nanomaterials in the PMMA composite [44,45], currently no references attempt to develop the PMMA composite with continuous carbon fibre.

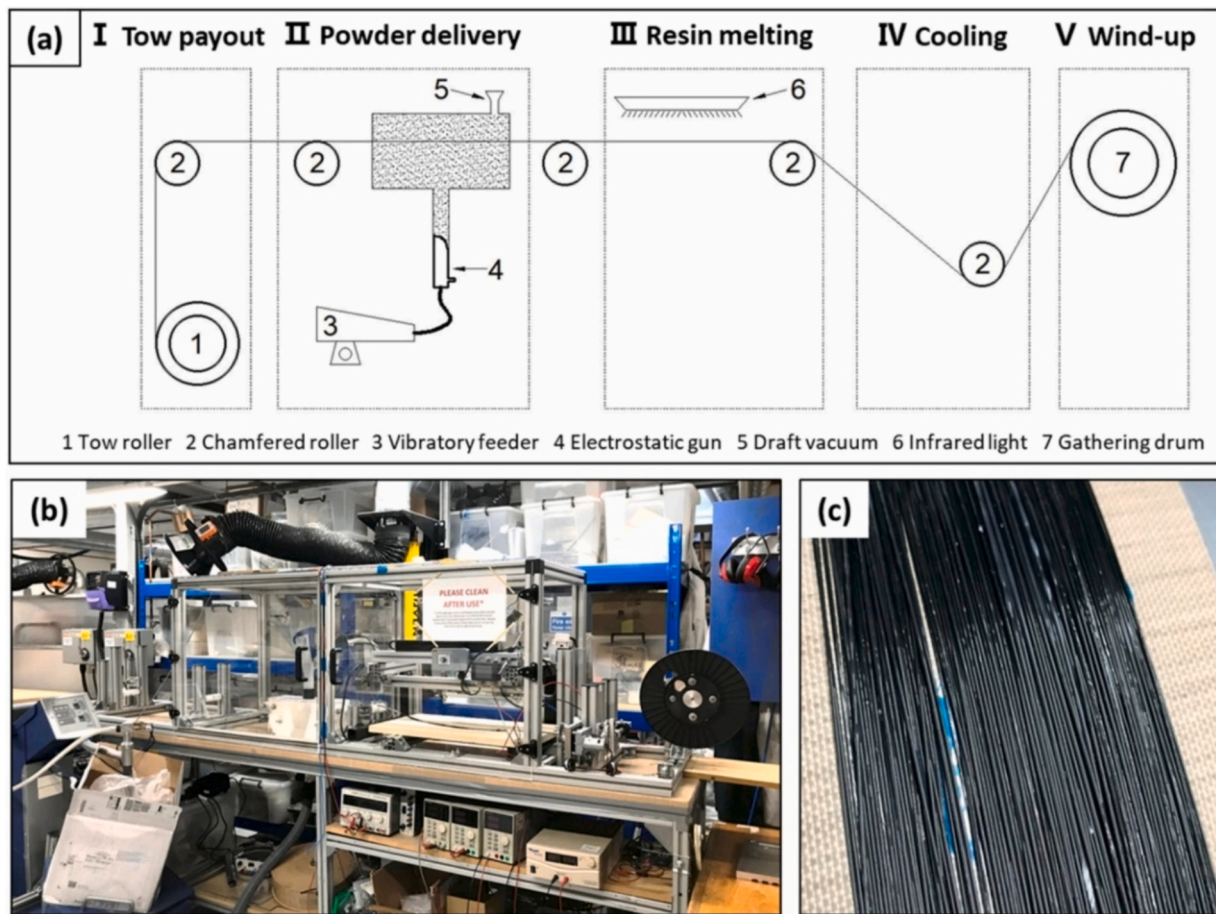


Fig. 4. Configuration of 3D printing process and the final product of continuous carbon fibre reinforced epoxy resin [41]

2.2.3. Polydimethylsiloxane

Due to its transparency, biocompatibility, low Young's modulus and high structural flexibility, PDMS has been widely used for the production of optical lenses, micromixers, microchannels and transparent pipes [46]. Khosla et al. [47] investigated the electrical conductivity of PDMS with carbon fibres of various fibre lengths and volume fractions. The percolation threshold decreased with the increase of fibre length, and the conductivity increased with fibre length at the same dosage. Zhang et al. [48] further modified the short carbon fibre filled PDMS with carbon nanofibers (CNF), to create a conductive network of dual-scale carbon fibres. Compared to the PDMS composite with a single carbon fibre, the hybrid composite displayed the most stable piezoresistivity without reducing stretchability. In addition, the carbon fibre yarns can be embedded with the PDMS matrix to manufacture a piezoresistive system by Montazerian et al. [49]. The strain along the yarns could be detected, indicating the conductive carbon fibre/PDMS composite was capable of being wearable devices for human motion detection.

2.2.4. Polylactic acid

PLA is a type of biodegradable material that has been increasingly used in injection molded products, bottles, drink cups, and medical absorbable suture, etc. [50]. Controlling temperature and pressure is critical to the formation of carbon fibre reinforced PLA with excellent mechanical properties [51]. In terms of the electromechanical properties, Luan et al. [52] employed continuous carbon fibre as sensory element in the glass fibre reinforced PLA composite. They observed that the piezoresistive composite could detect both the monotonic and cyclic flexural loadings without the degradation of flexural strengths. At a three-point bending test, they also observed a decreased change of

resistance when the loading position got far away from the central point, because of the decreased induced strain [53]. Besides, by incorporating continuous carbon fibres, PLA is often used as a matrix polymer in 3D printing for the preparation of multifunctional shape memory composites and conductive self-sensing composites [54].

2.2.5. Polyetheretherketone

Reinforced continuous CF composites with thermoplastic poly-ether-ether-ketone (PEEK) matrix have gained particular attention on account of their excellent thermomechanical characteristics. This high-melting ($\sim 343^\circ\text{C}$) semi-crystalline polymer usually exhibits a glass transition temperature (T_g) at $\sim 143^\circ\text{C}$ and represents an exceptional candidate for the production of high-performance structural components as metallic replacements [55]. Additionally, PEEK offers the flexibility of processing with various manufacturing techniques such as 3D printing, except for the conventional e.g. injection molding [56]. However, poor impregnation of the continuous CF is still an open challenge and many research groups try to optimize the interface bonding [57]. For instance, Meng et al. developed a pre-heating procedure step with laser (Fig. 5a) in order to improve the impregnation of CFs during extrusion 3D printing [55]. Tehrani and co-workers [58] investigated the influence of hot isostatic pressure upon the 3D printing of a continuous CF/PEEK composite. More analytically, isostatic pressure (200 psi) and elevated temperatures were combined to compress internal voids, promote PEEK crystallization, enhance inter-filament polymer diffusion and this post-processing was found to improve flexural and interlaminar shear strength up to 46 % and 30 %, respectively. Recently, Dai et al. reported a compression molded high CF volume fraction (66 wt%) reinforcement composite within a PEEK matrix presenting improved mechanical and

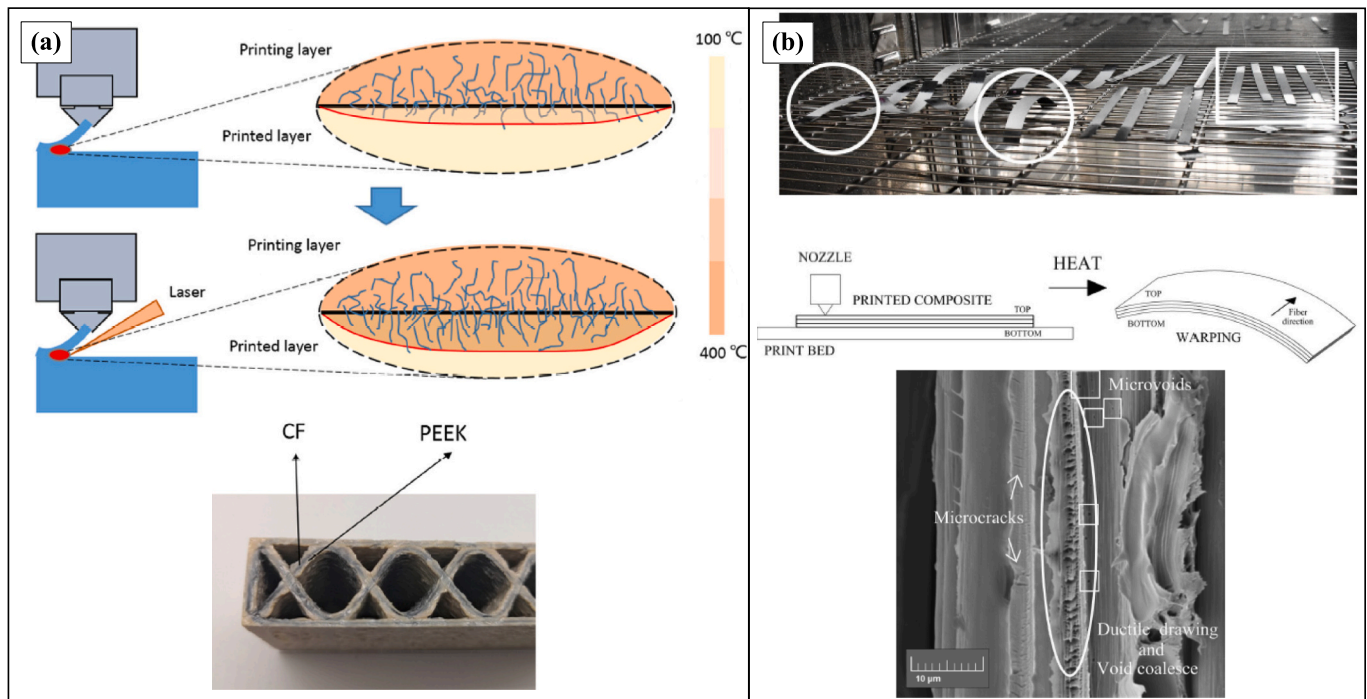


Fig. 5. (a) Schematic representation of the proposed laser pre-heated impregnation assistance method and the corresponding real continuous CF/PEEK 3D printed component. Reproduced with permission [55]; (b) longitudinal and transverse tensile CF/PA specimens in the climate chamber for hygrothermal aging, schematic depiction of warping direction of 3D printed transverse specimens and SEM micrograph of wet transverse CF/PA composite showing void coalesce and ductile drawing. Reproduced with permission [60].

wear capabilities, especially for high temperature applications. The ultra-high mechanical properties are attributed to a superior interface bonding and the enhanced friction wear feature resulted from a self-lubricating effect between CFs and PEEK particles at composite level [59].

2.2.6. Polyamide

Thermoplastic engineering Polyamide (PA) polymers possess low density, high strength, heat stability and have been incorporated with continuous reinforcing CF in order to produce lightweight structural units employed in aeronautics, automotive and other civil engineering applications e.g. reinforcing of concrete masonry building [61]. Aliphatic Polyamide is known as nylon and aromatic Polyamide is referred as aramid. Moreover, Polyamide polymers present good transparency, rigidity, hardness, chemical resistance, and moisture absorption properties with a T_g at around 47 °C. In particular, semi-crystalline Polyamide-6 has been extensively utilized as a thermoplastic matrix for CF composites [62]. Kikuchi et al. studied the moisture effect on the mechanical properties of continuous CF/PA 3D printed composites (Fig. 5b). More specifically, the experimental results revealed that moisture significantly affects the interface bonding between printed filaments resulting in a decrease of the mechanical properties in the saturated state, including those in the fibre direction. Furthermore, a permanent degradation was visible in some cases after the drying stage [60]. Chabaud et al. explored the potential of continuous CF/PA 3D printed composites for outdoor structural applications through extended hygromechanical characterization. More precisely, the hygromechanical behavior correlated with the moisture effect was investigated through sorption, hygroexpansion and mechanical tests on a wide range of relative humidity (RH) 10 to 98 %. The printing process induced an original microstructure with multiscale singularities and the longitudinal tensile performance revealed a typical reinforcing mechanism of CF reinforced composites. On the contrary, the poor transverse properties were not fitted by the rule of mixture, thus underlining the specificity of the printing-induced microstructure and an anisotropic character within

the composite volume. Moreover, non-negligible (5–6 %) moisture uptake was observed at 98 % RH, coupled with an orthotropic hygroscopic expansion of CF/PA composites. As a result, a reduction of 25 % stiffness and 18 % strength in the longitudinal direction and 45 % and 70 % in the transverse direction was reported [63]. Garmestani and collaborators proposed a synergistic reinforcement of continuous CF/PA laminate composites with short CFs. The deformation and failure mechanisms of the 3D printed laminated composites were assessed in relation to the morphological evolution and the results showed a separated distribution of continuous CF layers loaded in the thickness direction with a highest flexural modulus and strength. On the other hand, for continuous $\pm 45^\circ$ CF/PA, a separated distribution of continuous CF reinforced layers loaded in the longitudinal direction presented the highest energy absorption [64].

2.2.7. Further matrices

Other matrices incorporated with carbon fibre to manufacture the electrically conductive composites consist of polyvinylidene fluoride (PVDF), silicone rubber, and nitrile rubber, etc. Dozens of articles have investigated the piezoresistive and sensory performance of PVDF modified with nanomaterials such as carbon nanotube, CNF, or carbon black (CB), but only a few studies have applied carbon fibre especially continuous carbon fibre [65–67]. Ho et al. [68] applied 15 wt% short carbon fibre to successfully increase the mechanical strength and stiffness of PVDF, while the research did not involve the electrical and piezoresistive properties. Ram et al. [69,70] explored the electrical and percolation threshold of PVDF containing 0.5 wt% short carbon fibre, and found that the fibre aspect ratio is critical to the electrical performances. For the silicone and nitrile rubber composites, Yang et al. [71] found 0.88 vol% short carbon fibre/silicone rubber composite increased its performance on mechanical strength, sensory properties, and electrical reversibility. Pramanik et al. [72] concluded that the nitrile rubber composites with 30 wt% transversely oriented carbon fibres performed better than their counterparts with longitudinally oriented carbon fibres on the piezoresistivity. In addition to the polymer matrix, the continuous

carbon fibre yarns have been coated with cementitious or geopolymer composites, to prepare the mineral-impregnated carbon fibre reinforcement (MCF). The MCF possessing higher resistance to chemical attack is expected to replace the traditional steel reinforcement in reinforced concrete structures [73,74]. Table 1 summarizes the above-mentioned polymeric composites reinforced with carbon fibres for multifunctional investigations.

2.3. Continuous carbon fibre composite

2.3.1. Unidirectional and crossply carbon fibres

The polymer matrix is usually a dielectric material, which can be rendered with excellent electrical conductivity by applying carbon fibre reinforcement. The arrangement of carbon fibre directly affects the generation of conductive paths and networks. Miller et al. [77] investigated the induction heating of carbon-fibre reinforced thermoplastics, and found that the electrical current transfers between the fibre layers. Therefore, they proposed that the unidirectional carbon-fibre laminates, which did not contain fibre junctions, cannot be induction heated. Similar conclusions have also been proved by Rudolf et al. [78]. They assumed that the junctions' quality and fibre contact length were critical to the induction heating. Chung et al. [79] investigated the effect of unidirectional and crossply continuous carbon fibres on the electromagnetic interference (EMI) shielding effectiveness of polymer composites. They observed that the fibres parallel to the electric field performed better than those transverse to the electric field on EMI shielding because a larger current was generated to strengthen the reflection. Moreover, the crossply polymer composites showed higher electromagnetic absorption than that of unidirectional composites. Furthermore, the studies by Zhou et al. [80] indicated that the polymer composite possessed the electromagnetic absorption capacity regardless of the subsequent fibre orientation, when the carbon fibres of the outer lamina were parallel to the electric field. They attributed the phenomenon to the high conductivity of carbon fibres in the axial direction.

2.3.2. Interlaminar interface decoration

The interlaminar interface means the boundaries between laminae of carbon fibres in a polymer composite. It is an interfacial transition zone in the unidirectional carbon fibre reinforced composite or a fibre joint in the crossply carbon fibre reinforced polymer composite. It has been demonstrated that the graphene oxide (GO) reinforced interlaminar interface increased 170.8 % fracture toughness and 108.0 % resistance of polymer composite [81]. Also, the properties of the interlaminar interface firmly relate to the contact resistance of laminae, the induced Joule heating, the thermal conductivity and piezoresistivity [82,83]. To improve the performance of the interlaminar interface and the thermal conductivity through the thickness direction (z-axis) of the polymer composite, Han et al. [84] applied CB nanoparticles to partially replace the insulating polymer resin between laminae. As displayed in Fig. 6, the small content of CB decreased the interface thickness while the thickness

increased with the increased concentration of CB and was even larger than the unmodified composites when the CB concentration exceeded 1.0 %. In general, the thermal conductivity and mechanical modulus were increased considerably by 210 % and 14%, respectively with dispersed 0.8 wt% CB. Similarly, Kong et al. [85] found that the contact resistance between laminae increased with the increase of ZnO nanorods, which led to an increase in temperature with an applied current. Besides, the added ZnO nanorods could act as a thermal barrier by reducing the rate of temperature decrease during cooling.

2.3.3. Carbon fibre enhancement

The interfacial adhesion between carbon fibres and the polymer matrix is of high importance for the mechanical and functional properties of FRP composite. Hence, multiple approaches have been made to modify the carbon fibre and to increase the interfacial properties of FRP composites, ranging from oxidation, chemical deposition, coating, to polymerization, or their combination etc. [86,87]. Jiang et al. [88] increased the surface roughness and wettability of electrochemically oxidized carbon fibre by combining deposited GO on the surface. The results showed that the interlaminar shear and compressive strengths of the modified FRP composites increased by 59.4 % and 12.8 %, respectively. The studies by Lai et al. [89] showed the improved interfacial and tribological properties of a continuous carbon fibre reinforced polymer composite, when the carbon fibres were deposited with carbon nanotube and GO. In terms of the multifunctionality, Bhanuprakash et al. [90] coated the carbon fibre with GO and obtained the FRP composites with improved interlaminar shear strength, and electrical conductivity. Zanjani et al. [91] compared the self-heating and deicing properties of FRP composites with graphene modifications on the surface of carbon fibres, epoxy matrix and on both surfaces of carbon fibre and epoxy matrix, respectively. They found that the graphene as a carbon fibre modifier and matrix reinforcement simultaneously could achieve the FRP composites with the best electrical conductivity and self-heating properties.

3. Influence of environmental factors

3.1. Temperature

Given the electrical resistivity of carbon fibre reinforced polymer composites is changed with temperature due to the changed electrons' energy, the influences of temperature on the electrical resistance, and especially the functional properties have been investigated. Fig. 7a-b illustrate the electrical signal changes of CFRP under cyclic temperature and temperature fatigue, respectively. Forintos and Czigan [92] studied the electrical resistance changes of carbon fibre roving inside glass fibre reinforced epoxy composite when the temperatures ranged from -20 to 120 °C. The corresponding changes of electrical resistance indicated that the continuous carbon fibre roving is capable of monitoring temperature changes in the working environment. Cao et al. [93]

Table 1

Summary of multifunctional carbon fibre reinforced polymer composites with various polymer matrixes, carbon fibre forms and electrical properties.

Functionality	Polymer matrix	Carbon fibre forms	Additional filler/content	Electrical Properties			Refs.
				Conductivity	Resistivity	$\Delta R/R_0$	
Thermal conductivity	Epoxy resin	Carbon fabric	Graphene oxide/6.3 vol%	0.18 S/cm	—	—	Senis et al. [75]
Strain sensing	Epoxy resin	Carbon fabric	CNF/0.5 wt%	—	—	~66 %	Wang et al. [76]
Electrical conductivity	PMMA	Short carbon fibre	—	10^{-1} S/cm	—	—	Starý et al. [44]
Wearable sensor	PDMS	Short carbon fibre	CNF/0.85 wt%	—	—	~5–8 %	Zhang et al. [48]
Strain sensing	PDMS	Short carbon fibre	—	—	—	> 500 % (in tension)	Montazerian et al. [49]
Stress sensing	PLA	Continuous glass fibre	Continuous carbon fibre	—	—	~3.5 %	Luan et al. [52]
Strain sensing	PLA	Carbon fibre tow	—	—	—	~0.5 %	Luan et al. [53]
Electrical conductivity	PVDF	Short carbon fibre	—	—	$10^6 \Omega \cdot \text{cm}$	—	Ram et al. [69]
Stress sensing	Nitrile rubber	Short carbon fibre	CB/60 wt%	—	—	~40 %	Pramanik et al. [72]

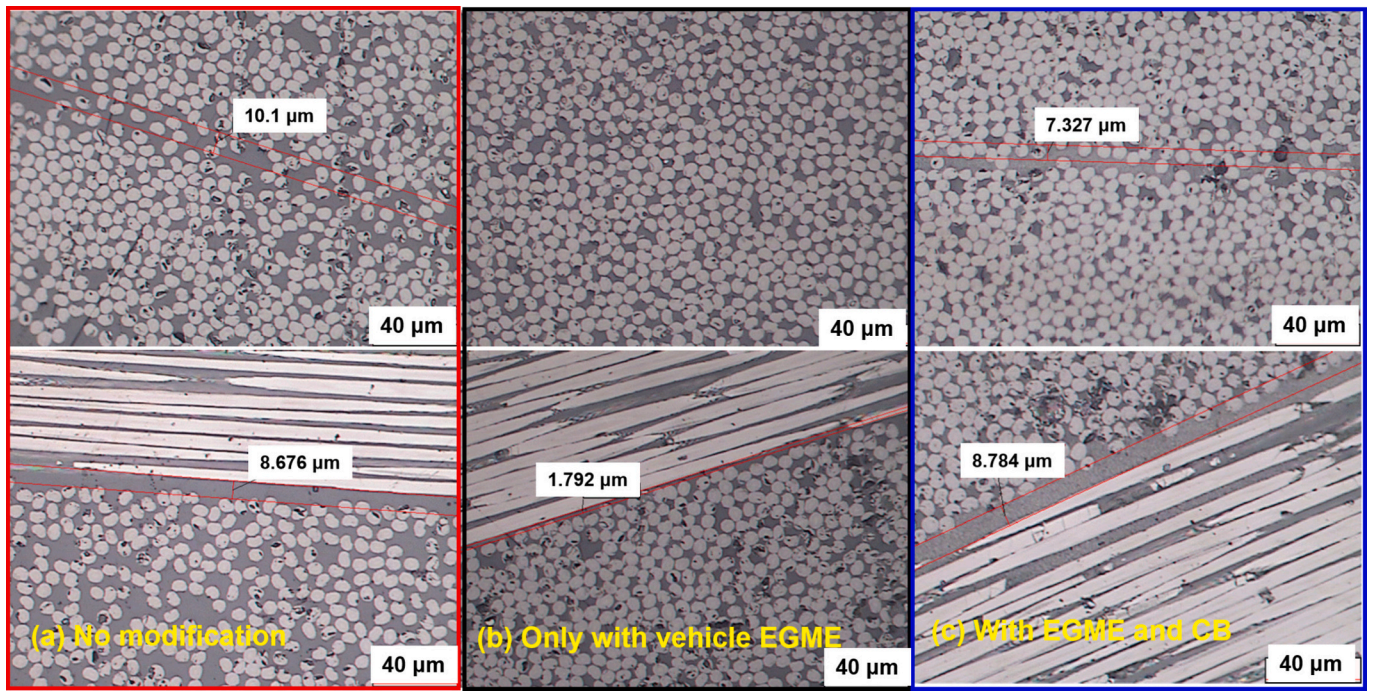
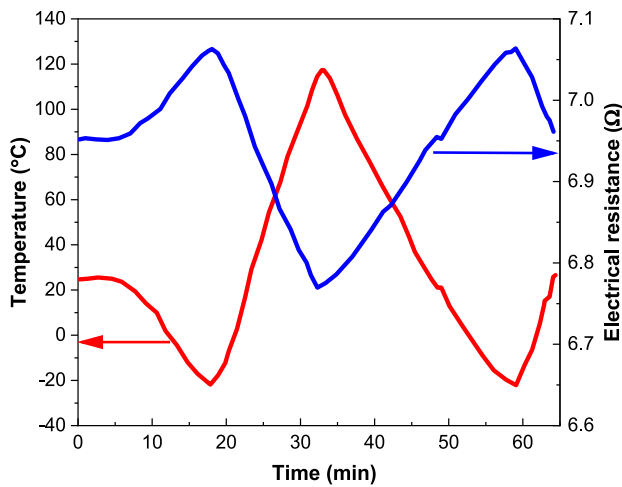
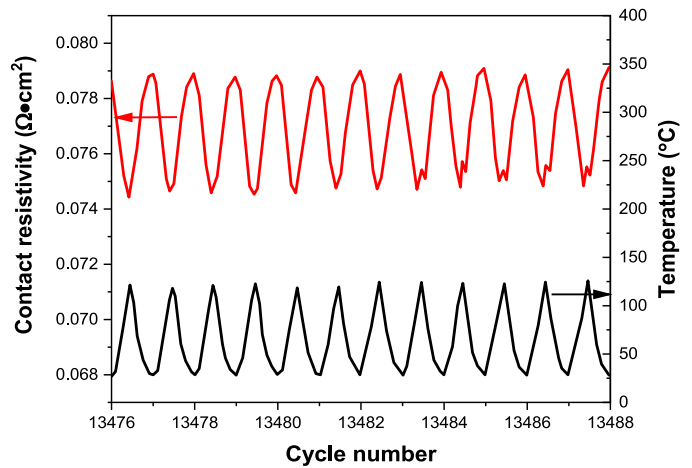


Fig. 6. Cross section of unidirectional and crossply laminates: (a) without modification; (b) only modified with ethylene glycol monoethyl ether (EGME) and (c) decorated with EGME and CB in the interlaminar Interfaces [84].



(a) Cyclic temperature change



(b) Temperature Fatigue

Fig. 7. Electrical resistance and resistivity of CFRP under cyclic changes of temperature and temperature fatigue [92,95]

explored the effect of temperatures between 30 °C and 600 °C on the dielectric properties, EMI shielding and microwave absorption of short carbon fibre filled silica composite. It was found that the electrical conductivity of composites increased with increasing temperature because of the shortened relaxation time of electron polarization, but the EMI shielding did not change greatly with the shielding effectiveness always larger than 10 dB. Similarly, studies have been conducted by Wandowski et al. [94] who investigated the influence of temperature on the electromechanical impedance of carbon fibre reinforced polymer panels for structural health monitoring. To reduce the temperature interference, they proposed an improved method by compensation of horizontal and vertical resistance signal shifts, respectively. Further, Wang and Chung [95] found that the electrical resistivity of carbon

fibre/epoxy composite reversibly decreased with increasing temperature, while the resistivity increased with thermal fatigue after a large number of cycles of temperature excursion. Based on the temperature interference, they proposed that the composite could be the sensor for the timely thermal fatigue monitoring by the resistance measurement. Some studies also mentioned the effect of temperature on electrical and functional properties, but the composite was either in a cement matrix or without carbon fibres [96–98]. Overall, more future studies should be focused on the temperature interference on the electrical and related functionalities of continuous carbon fibres reinforced polymer composites, and especially the approaches for elimination.

3.2. Humidity

The effects of humidity on the electrical properties of CFRP composites are not only due to the free ions in the pores and the moisture around CF that affect the generation of conductive paths and contact resistance, but also due to swelling effects by the polymer matrices that alter the distance between conductive carbon fibres [99]. Wang et al. [100] found that the electrical resistivity of continuous carbon fibre reinforced polymer composites could reversibly change with the cyclic alteration of relative humidity. The changing rate of electrical resistivity is approximately 0.7 % with the altered relative humidity ranging from 10 to 90 %. Similarly, Forintos and Czigany [92] found the insignificant effect of relative humidity from 20 to 95 % on the electrical resistance of carbon fibre roving reinforced polymer composite, with the electrical resistance changing rate within 0.5 %. For the studies with a narrower relative humidity from 30 to 90 % by Górski et al. [101], the electrical resistivity changes induced strain error of the continuous carbon fibre strain sensor reached nearly 0.06 %, which could also be considered as the changes of electrical resistivity of carbon fibres themselves. Moreover, they observed at least one hour delayed resistivity changes to the changed humidity, due to the time-consuming process of the moisture exchange between composites and air. The delayed changes of electrical signal could be observed from the other studies, which is especially evident when the humidity reached the largest percentage, but the electrical resistivity needed hours to reach the peak [94]. However, it is odd that the resistivity decreased simultaneously with the decrease of relative humidity, probably due to the thin thickness of the CFRP film. In terms of a smaller range of relative humidity changing from 30 to 80 %, the largest electrical resistivity changes of 23 % were found by Chen et al. [102], but the changes originated only from the carbon fibres themselves without any matrix. Many other studies also investigated the electrical resistivity changes of carbon fibre reinforced polymer or cement composites under multiple humidity or water content environments [86,103,104], demonstrating that the continual carbon fibre reinforced polymer composites do have the capacity to be one of the humidity sensors for environmental or damage monitoring.

3.3. Corrosive environment

Studies have attempted to investigate the chemical-electrical response of concrete with carbon fibre reinforced polymer as surficial coating in a chloride environment. They found a responsive electrical signal of concrete with different polymer coverage from 0 to 100 %, but did not measure the electrical signal of carbon fibre reinforced polymer itself. The micromorphology of carbon fibres before and after immersion in NaCl solution, the residual sodium chloride crystals implies that the electrical properties of carbon fibre reinforced polymer could be altered in a corrosive environment, which laid the foundation for its sensory application [105–108]. Also, studies by Li et al. [89] found that the epoxy resin could be cracked and the adhesion to carbon fibres decreased with the degradation in seawater. Although the electrical properties of the polymer were not involved, it could be easily deduced that the electrical conductivity of carbon fibre reinforced epoxy resin was altered after the corrosion treatment due to the transformation of the contact between fibres and matrix. Currently, the durability exploration of carbon fibre reinforced polymer mainly focuses on the protection performance when they are applied with concrete or steel reinforcement [109], and very limited studies have applied CFRP composites for the health monitoring in corrosive environments based on the alteration on electrical signals. It is worth noting that studies addressing the coupled effects of temperature, humidity, and corrosive environments on the electrical and multifunctional properties of CFRP composites are currently rare, and thus more explorations are encouraged in terms of the multifunctional CFRP in real-world environments.

4. Self-sensing properties

To evaluate the self-sensing capabilities of CFRP composites in realistic applications, various mechanical loading conditions, including compression, tension, flexural, impact and fatigue, are considered in this section. These loading modes are commonly encountered in civil infrastructure elements such as bridge decks, columns, beams, and retrofitted concrete components, where CFRPs are subjected to diverse stress states throughout their service life. By investigating the piezoresistive responses of CFRP under different loading scenarios, researchers aim to simulate practical service conditions and assess the reliability of CFRP as a structural health monitoring material. The following subsections summarize experimental methods and findings under each loading type, highlighting how the electrical response of CFRP correlates with mechanical deformation and damage progression.

4.1. Compressive load monitoring

Since CFRP composites are mainly used due to their tensile properties, compressive load monitoring with CFRP composites is rarely investigated. Fig. 8 exhibits the displacement of carbon fibres in the fibre direction when compressed by axial forces. A continuous carbon fibre reinforced polymer in a honeycomb structure was studied by Ye et al. [110], in terms of the electrical resistivity and self-sensing performance under cyclic compression. Similarly, another study by Wang and Chung [111] investigated the electrical resistivity and piezoresistivity of continuous carbon fibre reinforced polymer in the through-thickness direction. In both of these studies, the electrical resistivity reduction under compression originates from the longitudinal contact between carbon fibres. The Poisson effect may play a minor role in the through-thickness direction, but generally the longitudinal resistivity changes are more significant than that in the through-thickness direction especially under tensile and flexural loadings.

4.2. Tensile load monitoring

Continuous carbon fibre reinforced polymer composites are widely investigated in regard to their tensile properties. Nanni et al. [112] studied the fractional changes of resistivity for the carbon fibre-glass fibre reinforced polymer rods subjected to monotonic and cyclic tensile stress, but the electrical resistivity changes had poor correlation to the applied stress with poor linearity and repeatability. Ramirez and Chung [113] firstly observed the viscoelastic stress-relaxation behavior of continuous carbon fibre tows in the process of an electromechanical tensile test. As a consequence, the electrical resistance could be decreased because of the rearrangement of carbon fibres as the tow relaxes. Further, Yang et al. [114] proposed a method of pre-tension of carbon fibre before impregnation in epoxy resin, attempting to reduce the misalignment and winding of carbon fibres. It was found that the tensile sensing performance of the polymer with carbon fibre tows was enhanced considerably when the strain of pre-tension was larger than 200 $\mu\epsilon$. Li et al. [115] investigated the relationship between tensile damage and alterations in electrical resistance in 3D braided composites under both monotonic and cyclic tensile loading conditions. As shown in Fig. 9, they observed distinct stages in the electrical resistance changes during monotonic tensile loading, characterized by three regions: a linear growth region, a transition region, and an exponential growth region. Each region corresponds to different modes of damage.

By incorporating CNF, Wang et al. [76] enhanced the self-sensing capacity and strain sensitivity of the carbon fibre reinforced polymer laminates, because of the additional conductive network formed by CNF. Also, many studies drew similar conclusions that the addition of carbon nanoparticles improved the electrical and self-sensing properties without degradation of mechanical properties [116–118]. In addition, Kalashnyk et al. [119] reported that the electrical and piezoresistive properties of carbon fibre bundles reinforced polymer were firmly

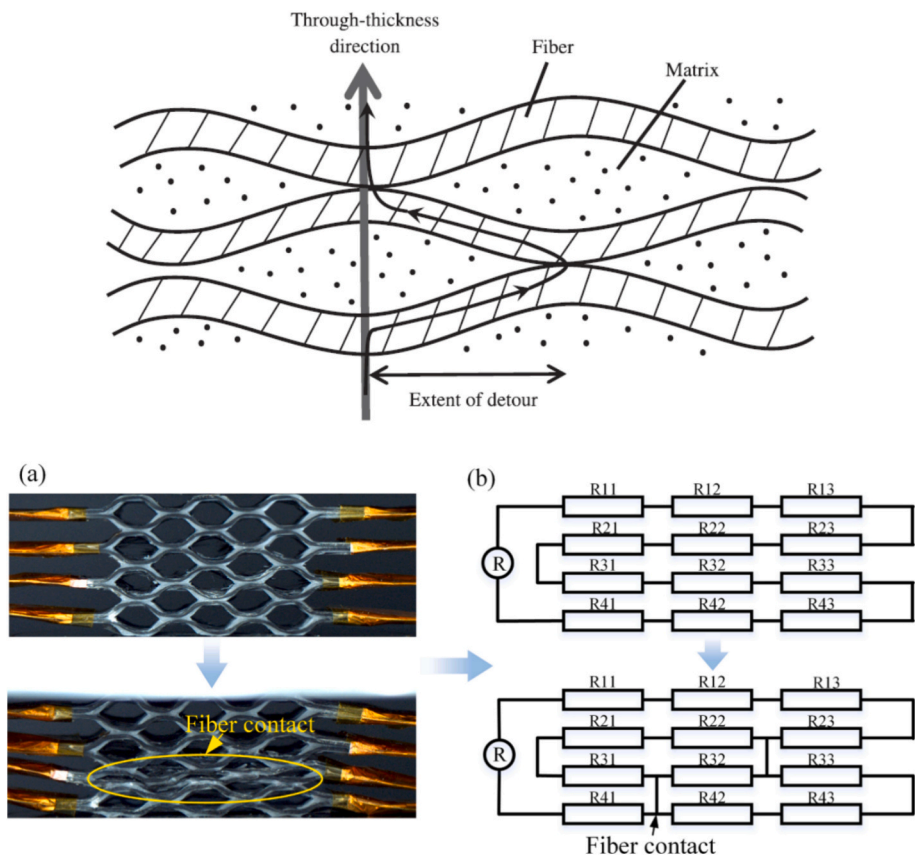


Fig. 8. Potential longitudinal contact between continuous carbon fibres under compression [110,111].

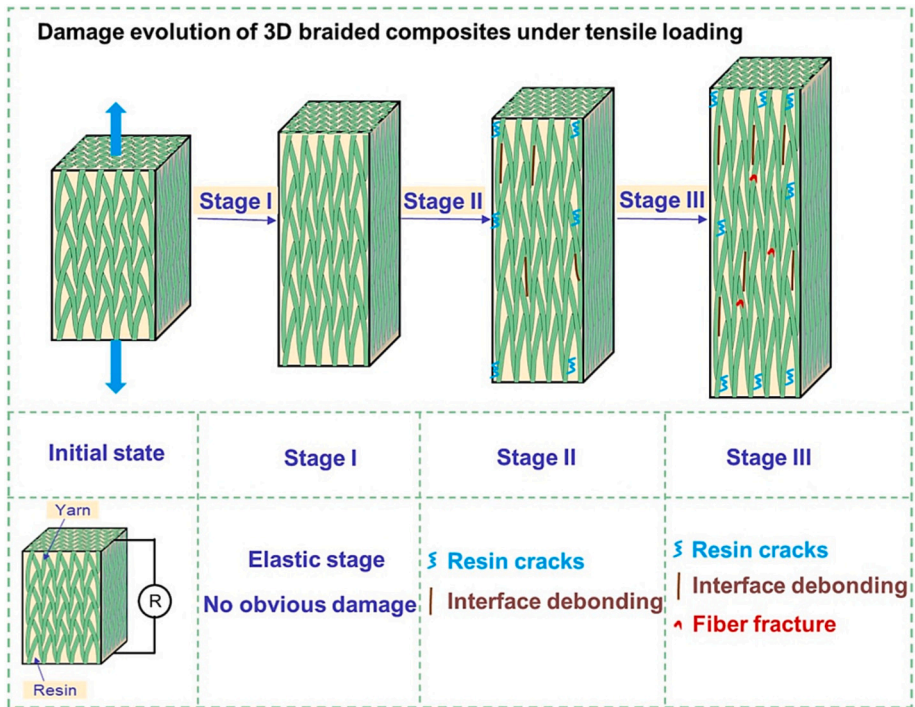


Fig. 9. Schematic diagram of damage evolution of 3D braided composites under tensile loading [115]

related to the thickness of the surrounding polymer layer and the surficial treatment of carbon fibres. The broken and fractured fibres were responsible for the increased electrical resistivity with the increased

tensile strain. Different from the previous studies that focused on the properties of carbon fibres or fibres reinforced polymer composites, Fouad et al. [120] investigated the application of continuous carbon

fibre reinforced polymer for the damage and health monitoring of concrete beams. The electrical resistivity changed correspondingly with the applied bending force on the beams, indicating its successful health monitoring of concrete structures.

On the other hand, the electrical resistivity of carbon fibres is able to alter differently under tensile test. The uncoated bare carbon fibre showed negative piezoresistivity with decreased electrical resistivity under tensile test, while the Ni-coated carbon fibre showed positive piezoresistivity. The positive piezoresistivity means that the electrical resistivity increases with increasing strain [121–123]. Considering the small positive piezoresistivity of nickel wire, the transformation is mainly due to the existence of nickel coatings that change the contact patterns of single carbon fibres.

4.3. Flexural load monitoring

The electrical performance of CFRP composites under flexural loading is unique because the changes of surface resistance are opposite to the compression and tension sides. Fig. 10 illustrates the deformation of CFRP and the electrical resistivity changes in the initial, elastic and damage stages under flexural test. Generally, the electrical resistivity increased in the tension zone and decreased in the compression zone with the flexural load [124–128]. Further, the studies by Zhu and Chung [129] found the better linearity of electrical resistivity changes to the loading regime, and proposed that the electrical signals generated from the compression zone were more appropriate as strain indicator. The electrical signal also relates to the loading point during the flexural test. By connecting the electrodes to the inner continuous carbon fibres, the studies by Luan et al. [53] obtained the increased electrical resistivity of composites under a three-point-bending test. The amplitude of electrical resistivity changes increased first and then decreased with the loading point moving from one side to another. The largest changes occurred when the loading point moved to the central zone of the entire composite. In addition, different flexural sensing performances were observed regarding the reinforced polymer composites with multiple numbers of fibres of carbon fibre tows ranging from 3 to 12 K. The ultimate flexural strength could be clearly improved with the increased number of carbon fibres, but it was difficult to distinguish the electrical differences of polymer composites reinforced with different number of

carbon fibres [130].

4.4. Impact and fatigue load monitoring

The other special loads applied on the CFRP composites for the self-sensing test mainly include the impact load and the load for fatigue damage. For the impact damage monitoring, Wang and Chung [132] measured multiple DC electrical resistance in axial, radial, oblique, and circumferential directions of composites subjected to drop impact load. The radial resistance decreased and the other resistance remained almost unchanged when the drop impact at 10 J or less. With larger impact energy, all the resistance increased due to delamination. Similarly, Todoroki et al. [133] applied three different drop impact energies of 14.1, 24.5 and 34.2 J on the continuous carbon fibre composites, the fibre damage and delamination cracks could be detected based on the captured voltage signal. In terms of the fatigue monitoring, Wang and Chung [134,135] firstly investigated the fatigue monitoring and delamination of carbon fibre polymer composites through electrical signals. The electrical resistance increased irreversibly because of the delamination due to fatigue. However, contradictory results were proposed by Baere et al. [136] who claimed that the fatigue damage could not be measured because no measurable damages were presented in their studies. Moreover, Todoroki et al. [137] found that the matrix cracking induced an increased electrical resistivity of carbon fibre reinforced polymer during fatigue test, while it could be compensated by the reduced electrical resistivity caused by shear-plastic deformation that hindered the matrix damage monitoring under fatigue test.

5. EMI shielding and anti-lightning strike capabilities

5.1. EMI shielding capability

The basic principle for EMI shielding investigations relies on the Faraday cage theory. When an external electrical field causes electric charges directly onto the cage's conductive framework this is distributed so that the applied field is canceled within the cage volume. The phenomenon transfer in daily practical applications is used to protect sensitive electronic equipment in specific building structures from external radio frequency interference [138–140] and also to prevent spontaneous

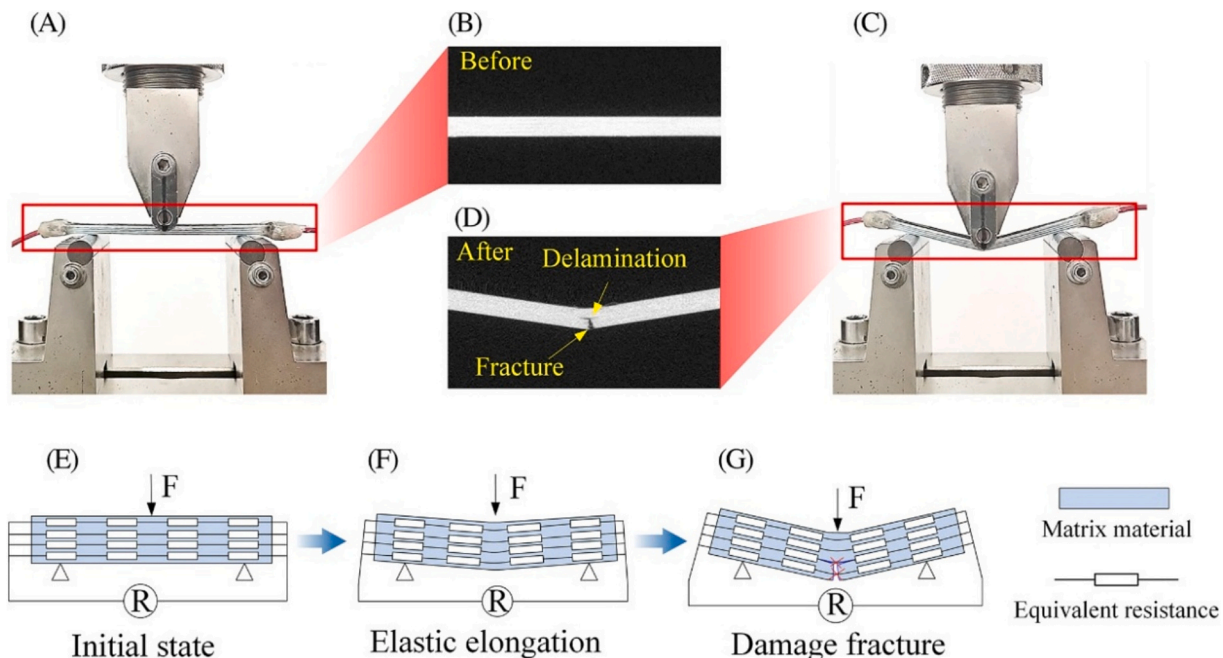


Fig. 10. Deformation and electrical resistivity changes of CFRP in different stages of flexural test [131]

electric currents e.g., lightning strikes or electrostatic discharges [141,142].

Carbon fibre reinforced polymer composites have been widely investigated and applied for EMI shielding to prevent modern vulnerable electronic devices from electromagnetic perturbation. Current studies involve the carbon fibres types and arrangements [143], with coatings [144], with nanofillers [145], continuous or discontinuous carbon fibres [146], 3D printable composites [147] etc. As summarized in Table 2, Zhao et al. [148] investigated the effects of different array spacings, the number of layers, and the overlap angle of continuous carbon fibres for the optimization of EMI shielding performance. For the frequency band of 30–750 MHz, the decrease of array spacing and increase of layers improved the shielding effectiveness (SE). Under a larger frequency of 750 MHz - 1.5 GHz, the carbon fibre orientation, rather than the number of layers was more considerable to affect the SE. It was also found that the continuous carbon fibre aligned in the direction of the electric field had the highest SE [149]. Similarly, Chung [79] proposed that the SE of carbon fibres transverse to the electric field was negligible compared to that of the fibres parallel to the electric field.

As an illustration, Hong and Xu investigated the EMI shielding anisotropy of CFRP laminates using a specified measuring set-up (see Fig. 11a). The electrical conductivity of unidirectional CFRP composites was strongly correlated with CF laminae orientations, as presented in Fig. 11b. Consequently, the EMI shielding anisotropy of unidirectional CFRPs resulted in the most effective EMI shielding value both experimentally, as well as theoretically (Fig. 11c). Technically, with a selected frequency of 15 GHz the CFRP specimen exhibited the lowest skin depth value of 0.035 mm in the 0° direction providing the mechanism for a tunable design of efficient EMI shielding CFRP composites [143].

Special conductive coatings on carbon fibre reinforced polymer composites perform better in EMI shielding. Chen et al. [150] deposited graphene oxide on the surface of carbon fibres and then reduced the graphene oxide with NaBH₄ solution. It was found that the reduced graphene oxide coated carbon fibre polymer composites could reach the SE value as high as 37.8 dB under the frequency of 8.2–12.4 GHz. By using the metal alloy of Ni–Co, Kim et al. [151] coated the carbon fibre with metal particles and obtained the modified carbon fibres with enhanced electrical conductivity. The coated carbon fibre polymer composite showed excellent SE values of 75–80 dB with the frequency of 1 to 1.5 GHz. Hu et al. [152] introduced the MXene nanoparticles onto the surface of CFRP by electrophoretic deposition. The flexural strength experienced a 26 % increase, while the out-of-plane electrical conductivity and electromagnetic interference (EMI) shielding effectiveness (SE) demonstrated a 66 % and 20 % improvement, respectively.

Moreover, the conductive nanofillers dispersed in the polymer matrix play a critical role in the enhancement of SE. Wu et al. [145] applied the Fe₃O₄ nanoparticles coated reduced graphene oxide to reinforced the polymer composites with continuously coated carbon fibres. The combined use of these conductive fillers provided the composites with the highest SE value of 51.1 dB at 26.5 GHz. The SE increasing rate reached 31.7 % compared to that of composites only with coated carbon fibres. Chen et al. [153] directly impregnated the continuous carbon fibres with Fe₃O₄ nanoparticles filled epoxy mixture, and concluded that the increase of Fe₃O₄ improved the total SE of composites. It was observed that the permittivity and permeability were enhanced by

Fe₃O₄ nanoparticles, to ameliorate the wave absorption capability of polymer composites.

Incorporating short carbon fibres with continuous carbon fibres to reinforce polymer composites has been rarely investigated. Hudnut and Chung [154] reinforced the layers of continuous carbon fibres with carbon filaments and obtained the composites with improved storage flexural modulus in the transverse direction. However, they did not mention the electrical properties and EMI shielding ability. Furthermore, Luo and Chung [155] observed that the application of short carbon fibres hindered the EMI shielding of continuous carbon fibre reinforced polymer composites. The potential reasons are not well presented in their study, but the degradation of the laminates and layers is one of the most likely possibilities.

Lately, Wanasinghe et al. [156] described the effect of CFs on the EMI shielding properties of geopolymers composites. This study focused on optimizing the CFs volume fraction and compaction within a sustainable geopolymers-based matrix to achieve the maximum shielding performance. Namely, a nominal value of 43.43 dB within a frequency range of 30 MHz to 1.5 GHz was reported.

5.2. Anti-lightning strike capability

Several research efforts have been dedicated aiming to increase the anti-strike protection of CFRP structures mainly for aerospace field applications. CFRP offer effective lightning strike protection while significantly reducing weight compared to traditional metal mesh [159]. Unlike metal mesh, CFRP provides superior corrosion resistance and design flexibility, making it a more durable and lightweight alternative for advanced electromagnetic shielding and lightning protection in modern infrastructure [160]. More specifically, Yue and co-workers developed a cold spray metallization process of pure tin and tin-copper coatings onto CFRP surfaces as a possible lightning strike protection solution. Lightning tests revealed that the cold-sprayed coatings provided sufficient protection to CFRP structures when subjected to currents up to 200 A [161]. Kumar et al. introduced the utilization of a low-cost CFs as cost-effective alternative for the lightning strike protection of wind turbine blades by effectively dissipating the lightning waveform current upon testing (Fig. 12a-b). The results proved a high resilience CFRP composite due to the achieved high electrical conductivity both in-plane and in through-thickness directions with no significant damage (Fig. 12c-d) after a lightning strike test [162]. Dydek et al. [163] proposed the seamless integration of a properly optimized continuous single wall carbon nanotube (SWCNT)-based film within CFRP structures for lightning strike protection, as a promising lightweight alternative for the commonly used copper mesh. Namely, a remarkable increase in the surface and the volume electrical conductivity by 8800 % and 300 %, respectively was recorded. Zhu and colleagues [164] designed a dual-layer lightning strike protection system consisting of a conductive layer and an insulating layer within the CFRP component. Finite Element modeling results were validated by experimental lab-scale lightning strike evaluation and the effects of different parameters for effective protection were systematically examined. Kopsidas et al. [165] explored a carbon black modification of the epoxy matrix, manufactured using resin-infusion under flexible tooling. The produced CFRP laminate presented significantly higher volume fractions, resulting in improved

Table 2
EMI shielding properties of polymer composites with continuous carbon fibres.

Polymer matrix	Number of CF	CF Treatment	Thickness (mm)	Frequency applied (GHz)	SE values (dB)	Refs.
Polyethylene terephthalate	12 K	–	1.98 mm	1.0	60.49	Zhao et al. [148]
Unsaturated polyester	12 K	Reduced GO coated	10	8.2–12.4	37.8	Chen et al. [150]
Epoxy resin	12 K	Ni-Co alloy-coated	1.5	1–1.5	75–80	Kim et al. [151]
Epoxy resin	12 K	Reduced GO coated	7.0	8.2–26.5	31.3–51.1	Wu et al. [145]
Epoxy resin	6 K	–	2.08	0.3 MHz to 1.5	114.8 ± 9.4	Luo and Chung [155]
Epoxy resin with GO	3 K	–	1.0	5–20	~58–83	Li et al. [157]
Unsaturated polyester	3 K	CNT coated	1.0	0.3–1.5	78	Gnidakoung et al. [158]

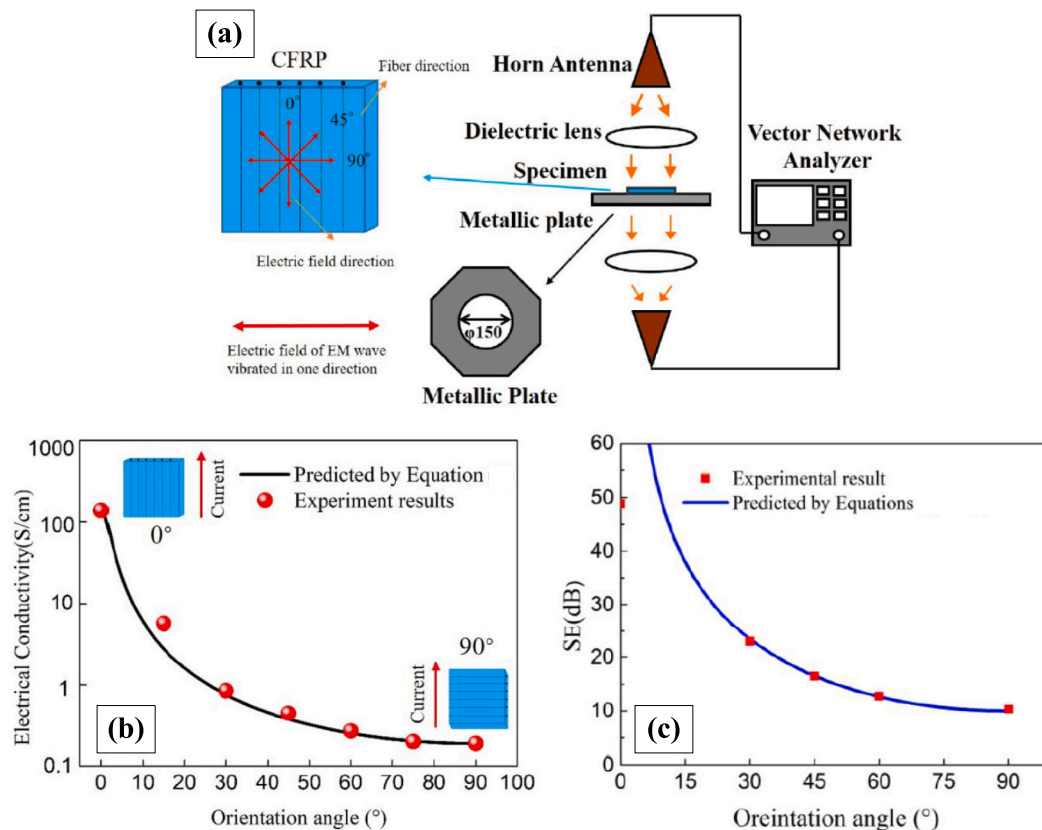


Fig. 11. (a) Scheme of the set-up for EMI measurements, (b) electrical conductivity and (c) shielding effectiveness values depending on various CF orientation angles of the examined CFRP specimen. Reproduced with permission [143].

electrical properties compared to a reference laminate manufactured by wet hand lay-up technique. Finally, the unidirectional CFRP laminate was subjected to a simulated lightning test with a current of 40 kA and only surface damage without any penetration was identified.

6. Self-heating and deicing potentials

6.1. Electric joule heating

The electrothermal effect also well-known as Joule heating, has been widely researched for various applications and in different areas [166]. In principle, resistive or Ohmic heating is the phenomenon when electric current is injected through an electrical conductor and accelerates charge carriers in the field direction generating heat owing to higher kinetic energy. At an atomic scale, this can be attributed to the inner interactions between electrons and ions within a conductor, where the particles are scattered due to multiple collisions and electrical energy is converted to thermal energy. Joule's first law describes that the generated heat by an electrical conductor is $P = I^2 R$, where P is power, I is current, R is resistance and the conversion of electrical power into heat equals $P = V^2/R$, where V denotes the applied input bias voltage [167].

The advantages of CFs in terms of electrical, thermal conductivity and physicochemical stability play a crucial role for their exploitation as effective heating elements highlighting again their potential for multifunctionality. Falzon et al. [168] exploited a novel electro-conductive carbon-based textile integrated within the outer surface of CFRP structures coupled with a glass fibre ply to avoid any electrical short-cut. The produced demonstrator was evaluated under multiple heating-cooling cycles and the introduced self-heating system yielded better heating rates for both deicing and anti-icing applications. Liu and co-authors presented an efficient self-resistive electrical heating method to rapidly in-situ repair CFRP parts [169]. A purposely developed portable

self-resistive electrical repairer with an automatic temperature control unit was used in comparison with a commercial electrical blanket heating for the repairing process. From comparative studies such as the degree of cure, the cross-section morphology and void content, flexural and interlaminar shear tests, a superior recovery ratio of self-resistive electrical repaired samples was pointed out. In Fig. 13a-b, a self-resistance electric heating configuration for the curing process of a CFRP laminate is depicted [170]. The rapid heating rate of the curing process resulted in a weaker matrix performance on account of insufficient time of void elimination, which leads to inferior compression and flexural strength. On the contrary, the fibre preferential heating effect significantly improved the fibre-resin interfacial strength due to naturally formed temperature difference along the interfacial area. Subsequently, enhanced tension and interlaminar shear strength values were acquired relying on this superior adhesive strength with the resin. Hirano and collaborators [171] introduced a self-heating approach for the enhancement of the relatively weak 3D printed lay-up direction. More precisely, 3D printed parts were produced via fused filament fabrication with a through-thickness rectangular hole and a rectangular reinforcing bar with continuous CFs was printed separately. Then, the reinforcing bar was inserted into the CFRP part through the hole and a voltage bias was applied through the reinforcing bar, where the thermoplastic matrix melted via resistive heating. In parallel, the reinforcing bar was partially fused into the 3D printed part, increasing its stiffness and strength in the lay-up direction, as was indicated by the corresponding mechanical tests. Recently, a new way based on electrical Joule heating was nominated for the early-stage strength acceleration of geopolymer-based MCF structures due to efficient thermal activation [172,173]. Well-established analytical techniques confirmed the advanced geopolymerization process with a flexibility for a variety of different shapes and dimensions (Fig. 13c-d).

Both electrically conductive and dielectric phases are needed for the

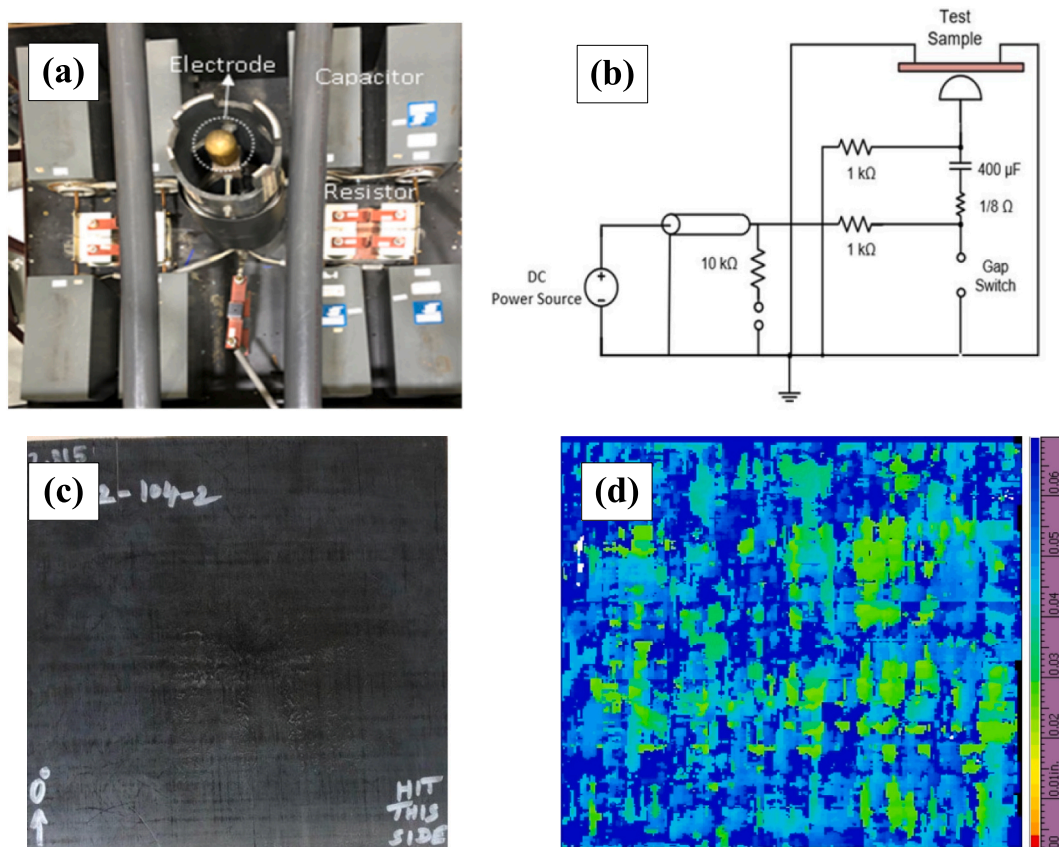


Fig. 12. (a) and (b) Lightning strike testing set-up and the corresponding equivalent circuit; (c) and (d) visual and C-scan surface inspection after a lightning strike test with 200 kA for the introduced CFRP sample. Reproduced with permission [162].

proper electrodes and insulation applications, respectively [174]. In particular, it is the interlaminar interface of two carbon fibre layers possessing a low electrical resistivity that could be applied as a self-heating element [82]. Table 3 lists the applied voltage, electrical resistance and current on CFRP composites and the changes in temperature during this process. The temperature distribution induced by Joule effect has been investigated by Shen et al. [175] on the continuous carbon fibre reinforced polymer. The parameter of mold size was found to be the most significant factor affecting the temperature distribution, because of the uneven heat absorption of the mold from the central region to the edge. One of the usages of self-heating is applied with shape memory materials for the shape recovery. Gong et al. [176] reinforced the shape memory polymer with continuous carbon fibre felt and obtained electrical-heating composites with low electrical resistivity. The shape recovery procedure of the polymer could be triggered within 15 s under electrical heating. Li et al. [177] conducted similar research by reinforcing the shape memory polymer with carbon fabric. The composites could be electrically heated above the transition temperature with improved deformation performance.

The most popular utilization of self-heating continuous carbon fibre reinforced polymer composites would be the heating elements for defrosting and deicing. Abbas and Park [178] investigated the frost melting times on the carbon fibre polymer fin with different voltage bias inputs, and observed the decreased melting time with increased heat fluxes. Ming et al. [179] applied the 3D printed continuous carbon fibre polymer for the deicing of wind turbine that decreased the deicing time by 85 % compared to the glass fibre reinforced polymer composites. Meanwhile, the mechanical properties of flexural strength and modulus, fibre to matrix bonding property and pore structure are all improved. Zanjani et al. [91] further modified the continuous carbon fibre reinforced polymer composites with graphene coating on carbon fibres and

graphene matrix modification. The modified composites showed 240 % enhancement on electrical conductivity, as well as improved thermal diffusivity. Moreover, Maleki et al. [18] embedded CFRP into a concrete slab and attempted to produce an electrically conductive concrete slab. It was found that the concrete slab under an external voltage of 3.75 V could increase the temperature of slab from -10 to 16 °C that was adequate for the pavement surface deicing. Similarly, Karalis et al. [180] proposed an electrothermal-enabled reinforcing grid based on the mineral-impregnated carbon-fibres (MCF), which could strengthen the geopolymer concrete surface as a reinforcement. The multifunctional reinforced concrete composite exhibited effective deicing capabilities when subjected to a DC voltage of 2.2 V. This voltage corresponds to a surface temperature of 45 °C, and remarkably, the required heating power was substantially low at 95.6 W/m² compared to similar research findings. Many other studies have utilized carbon fibre in conductive concrete for multifunctional applications [181], and this aspect will not be mentioned here particularly. Besides, some similar studies also attempted to utilize the electrical heating for the deicing of aircraft [182], electrical heating-based matrix system thermal curing [157,170] and rapid repairing or bonding of carbon fibre reinforced polymer parts [169].

6.2. Induction heating

Induction heating of CFRP appears when the materials are exposed to an alternating electromagnetic field of kilohertz to megahertz frequency range. The induced eddy currents and magnetic polarization effects are all basis of heat energy. However, the heat generated by eddy currents dominates in general applications [183]. It should be noted that a precondition for the generation of eddy currents in CFRP is the formation of electrical loops. Thus, fibres are more prone to be used in woven

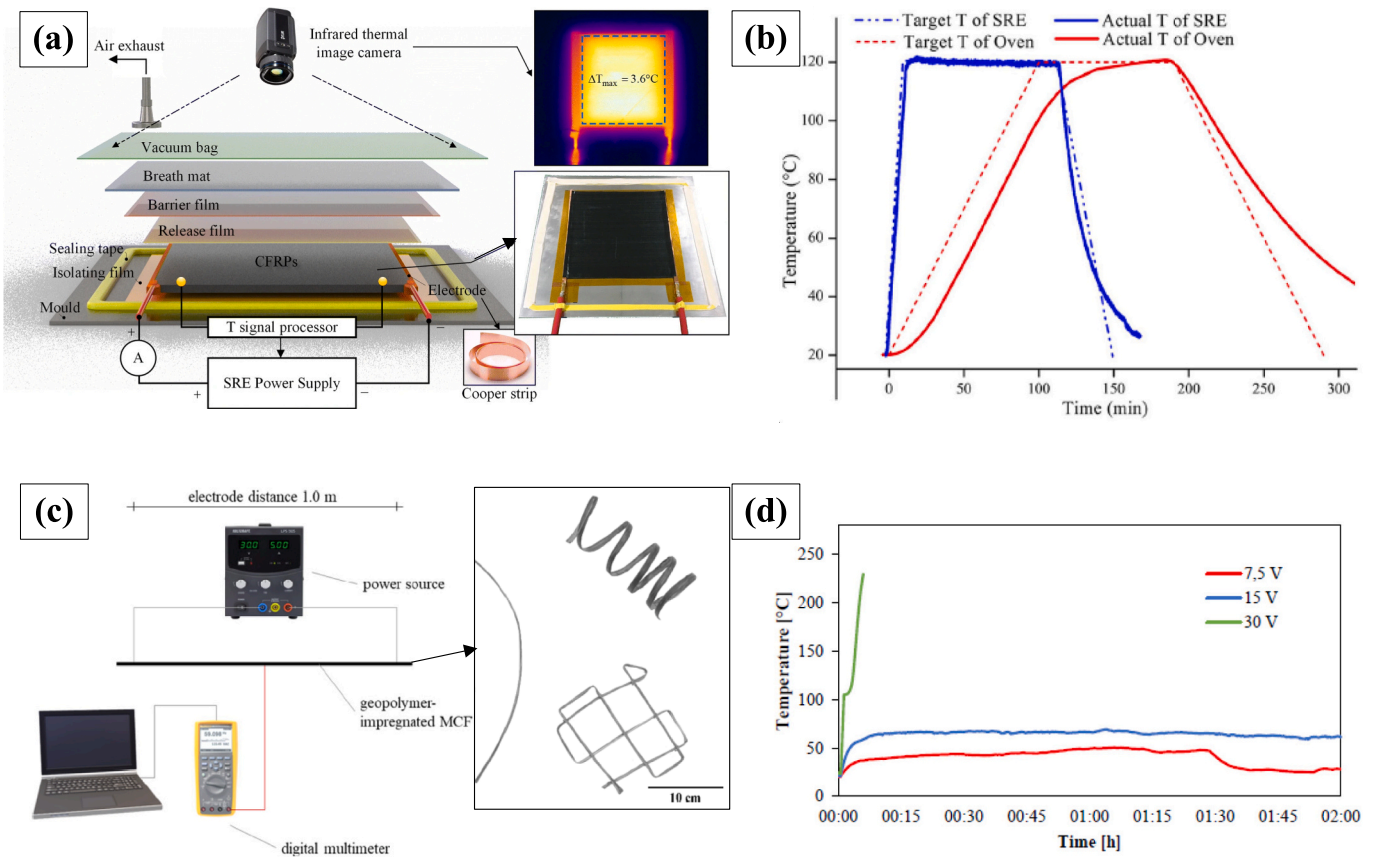


Fig. 13. (a) Schematic and real CFRP self-resistance electrical heating for laminate curing and (b) temperature curves during curing process for the self-heating and for the oven case, respectively. Reproduced with permission [170]; (c) electrical heating experimental configuration for the direct curing of MCF structures at various shapes and (d) the corresponding temperature profiles with respect to the applied voltages. Reproduced with permission [172].

Table 3

Electrical heating performance of polymer composites with continuous carbon fibres.

Polymer matrix	Shape	Resistance/resistivity	Voltage applied (V)	Current (A)	Temperature (°C)	Refs.
Epoxy resin	Interlaminar interface	0.25 Ω	0.53	2.1	85	Fosbury et al. [82]
Epoxy resin	CF felt laminate	2.019 Ω -cm	25	–	130	Gong et al. [176]
Styrene resin	CF fabric plate	29.6 Ω	45	–	90.9	Li et al. [177]
Epoxy resin	CFRP laminate	–	2.0	7.8	~110	Abbas and Park [178]
Epoxy resin	CFRP mesh	0.75 Ω	$P=U \cdot I=70$ W	–	170	Ming et al. [179]
Epoxy resin	CFRP laminate	–	0.18	1.0	40–70	Zanjani et al. [91]
Epoxy resin	CFRP prepreg	–	$P=U \cdot I=80$ W	–	154.1	Liu et al. [170]

or non-crimp fabric form, where in the latter case cross-ply laminate piles are preferred [184]. Then, the induced eddy currents cause electrical losses and permit rapid local intrinsic heating of the laminates.

The mechanism of induction heating of CFRP is divided into three parts, which are summarized as Joule losses of the fibre, dielectric heating at fibre junctions, and contact resistance at junctions [185]. As shown in Fig. 14a, Joule losses appear because of the electrical resistance when eddy currents run along the CF. This mechanism requires a low contact resistance between crossing fibres to guarantee the conductive loops [186]. In contrast to the Joule losses, the heat due to the contact resistance occurs at the junctions of CF [187]. The contact resistance depends on the contact area as well as contact resistivity and can be determined by the test methods. The third type of heating mechanism is dielectric losses at the junctions. In this case, carbon fibres at junctions are not in physical contact. The voltage difference between fibres evokes an electric field. Then the thin matrix layer separating the CF junctions acts as a dielectric. Therefore, dielectric losses occur in the polymer matrix between the CF [188]. The answer to the question, which of the three heating mechanisms is the most dominant, remains

open. Barazanchy et al. used numerical simulations to reveal the heating mechanism on the laminate level and fibre level. Results show that the highest heating is generated by either Joule losses and fibre contact, or both, in the former cases, while Joule losses mainly contribute to the latter case [189].

The main factors influencing induction heating include the coil, laminar structure, and polymer matrix. The increase of the induction power or decrease of the coupling distance might lead to partial overheating between the matrix and the susceptor [190]. The high-frequency generators are less efficient due to the losses in mountings and the frequency-dependent coil impedance. All these factors are related to the coil geometry (shape and number of turns), which can directly influence the spatial distribution of the magnetic field and consequently the distribution of the temperature in the CFRP laminate [187]. An example of the experimental setup to investigate the different parameters in the induction heating experiment is shown in Fig. 14b. Moreover, Kidangan et al. studied the influence of interlaminar microstructure on the patterns of induction heating, as illustrated in Fig. 14c. The pattern of induction heating shifted and the ratio of junction heating to fibre heating

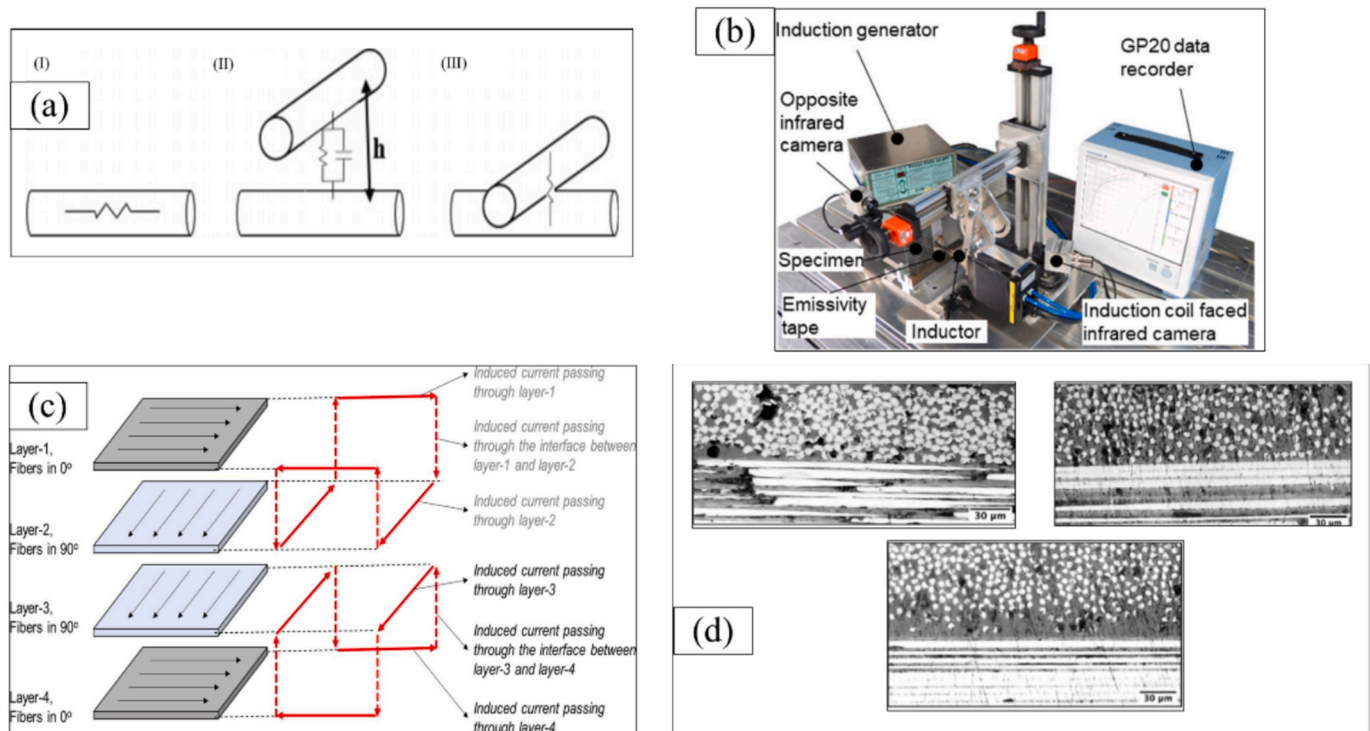


Fig. 14. (a) Induction heating mechanisms: (I) Joule losses, (II) Joule and/or dielectric polymer heating, (III) contact resistance heating [189]; (b) Experimental setup of the induction heating experiment [187]; (c) Schematic representation of fibre layers along with the flow of induced currents [191]; (d) Optical microscopic image of three different laminates at 500× magnification [191].

increased as the interlaminar distance increased [191]. Becker et al. studied the influence of different polymer matrix systems on induction heating, as shown in Fig. 14d. It was found that the dielectric properties of the polymer matrix have no significant effect on the induction heating behavior of CFRP composites, and the dominant heating mechanism depends on the magnitude of contact resistivity at the cross-junctions [187]. Lundström et al. found that the type and volume fraction of carbon fibre are of great importance for the electrical and thermal properties. The experiments indicate that a fibre volume fraction exceeding 60 % is necessary to achieve an isotropic uniform induction heating pattern [192]. In addition, nano carbon black is incorporated into carbon fibre-reinforced geopolymer to produce composites known as NCB-carbon fibre co-modified geopolymer. These composites exhibit significant potential for enhancing the electrothermal performance of electrically conductive layers and concurrently minimizing CO₂ emissions during induction heating processes [193].

Applications such as welding, curing, quality monitoring etc., can all be achieved by the induction heating of CFRP. CFRP induction welding is characterized by the heating of the bonding above their respective melt temperatures and bringing them into contact. The CF used as a susceptor is placed directly in the bonding zone in an ideal case. Fig. 15a presents the induction heating weld and the temperature development during spot welding. Then, the joint is cooled under pressure until the polymers reconsolidate [194]. Induction heating can also cure thermosets by reaction activation [195]. The intention lies in reducing the curing time. Frauenhofer et al. used induction heating of CF to bond CFRP panels by a thermoset adhesive and curing, as shown in Fig. 15b. The two-sided heating of the adhesive is feasible by using a single coil and the curing time is reduced to a minimum of 4 min [196]. In addition, the thermal response of CFRP heated by induction can also be studied to detect flaws as a kind of nondestructive testing. Bui et al. compared the experimental and simulated results of the surface temperature distribution. The developed 3D thermomagnetic model can be used to study the thermal inductive method for different kinds of flaws, inductors, and

frequencies (Fig. 15c) [197]. Moreover, the thermography technique based on induction heating can be used to characterize electrical conductivities. The thermal effect of electromagnetic phenomena recorded by the infrared thermal camera, as illustrated in Fig. 15d, can be used to better observe the dispersion of the induced electromagnetic field in the anisotropic material [198].

However, the application of this technology is still hindered due to the complex temperature distribution within the laminate, which results from the distribution of the magnetic field intensity and the orthotropic electrical laminate properties [199,200]. Understanding and predicting the heating pattern is therefore an important step toward an industrial solution. Researchers tend to use numerical methods to investigate the temperature distribution of CFRP. Fu et al. established the induction electricity-magnetic-eddy current-temperature multi-field coupling analysis model of plain weave CFRP based on the finite element mesoscopic model. The heating history and temperature distribution of carbon fibre composite materials were analyzed [201]. Lundström et al. modeled CFRP as a network of discrete resistors and computed the temperature distribution by the finite difference method (shown in Fig. 15e), thereby allowing a better understanding of the heating pattern [202,203].

7. Energy harvesting and storage concepts

Energy harvesting technologies can permit the direct conversion of diverse renewable energy sources (e.g., mechanical, chemical, thermal, etc.) existing in the natural environment into reusable electrical power [204–208]. The self-powering approach is a new paradigm for truly achieving energy-autonomous systems, which are of critical importance for sensing, medical science, infrastructure/environmental monitoring, defense technologies and even personal electronics. Practically, utilizing structural CFRP laminate composites as harvesters with or without a step-up boost converter driving the DC voltage produced in a capacitor, could enable the powering of low-consumption electronic devices

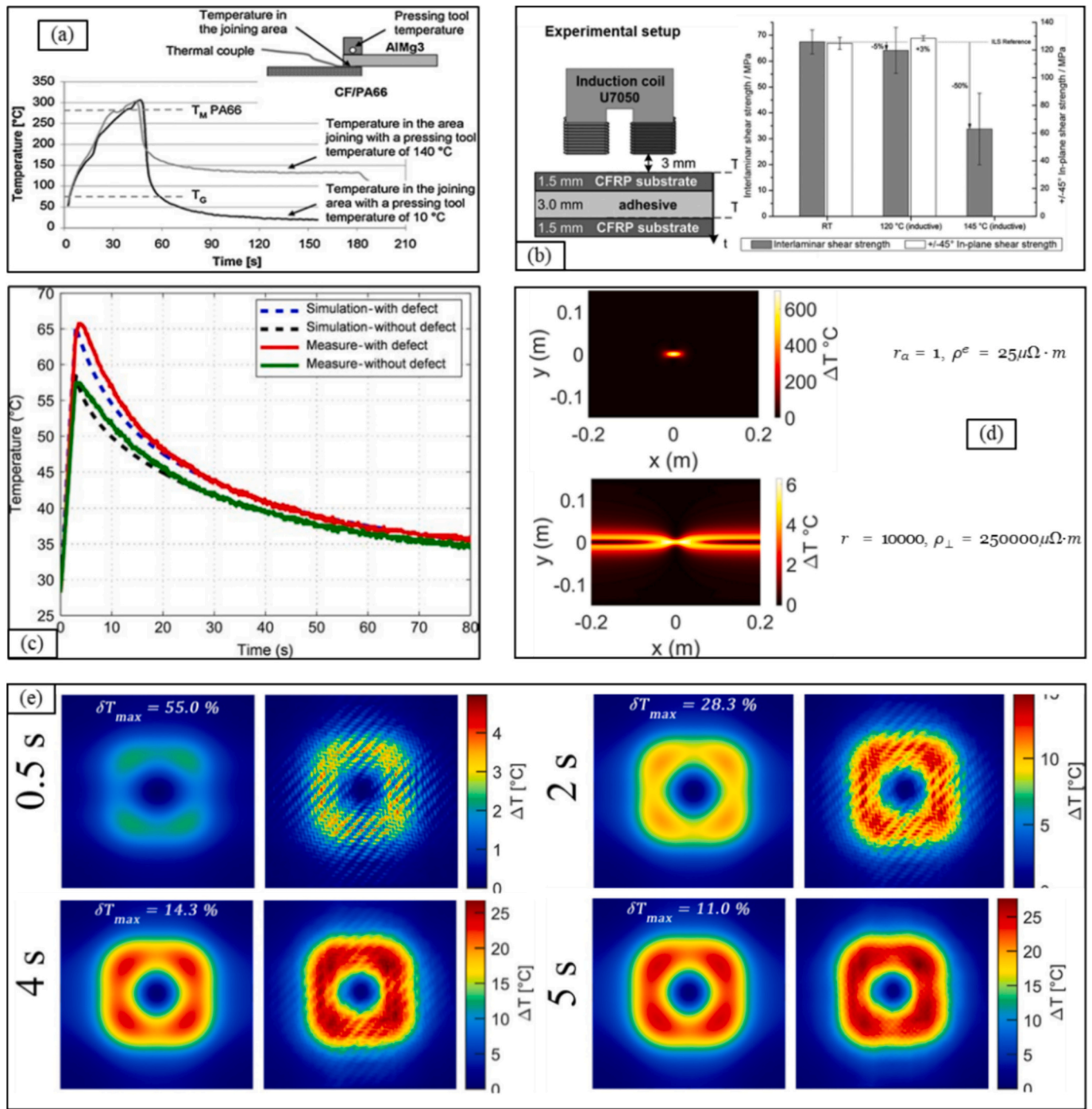


Fig. 15. (a) Schematic illustration of induction heating weld and the temperature development during spot welding in [177]; (b) Experimental setup for curing of adhesives in the field of CFRP and interlaminar shear strength after different inductive heating cycles [179]; (c) Application of inductive nondestructive testing method applied to CFRP: Evolution of temperature at the hottest point in the defected zone [180]; (d) Simulation results of the temperature obtained on a unidirectional CFRP due to the different anisotropy ratio of the material [181]; (e) Comparison between computation (left) and measurement (right) of the CFRP surface temperature at five different timestamps [185].

integrated in various infrastructures e.g. ultra-low power micro-controllers, wireless sensor networks (WSNs) or more sophisticated devices in the era of Internet of Things (IoT) applications etc. [209].

The piezoelectric effect is a phenomenon in which a voltage is generated on the basis of the strain produced when mechanical loads are applied to quartz or specific types of ceramics. Based on the aforementioned effect have been developed various types of sensors, as well as a potential for vibration energy harvesting which can be directly converted in a form of electric energy [210]. As summarized in Table 4,

Narita et al. [211] developed a potassium sodium niobate (KNN) nanoparticle-filled epoxy interlayer with Copper (Cu) electrodes sandwiched between two CFRP laminates (Fig. 16a-b). The depolarization during the curing process significantly affects the expected piezoelectric properties and thus a large electric field was applied by corona discharge which polarized the composite. The resulted demo was able to produce a power output of $0.8 \mu W/cm^3$ from impact loads. Lindbergh and co-workers [212] introduced a structural energy harvesting CFRP consisting of two CF laminae embedded in a structural battery electrolyte (SBE)

Table 4

Highlights of multifunctional CFRP composites with energy harvesting and energy storage characteristics.

Demo	Dimensions	Power output	Capacitance	Year	Reference
CFRP piezoelectric harvester	40 × 10 × 0.5 mm ³	0.8 μW/cm ³	–	2020	Wang et al. [211]
CFRP piezoelectrochemical harvester	42 × 15 × 1.5 mm ³	18 nW/g	–	2022	Harnden et al. [212]
CFRP triboelectric harvester	40 × 50 × 1 mm ³	8.36 μW	–	2020	Liu et al. [219]
CFRP thermoelectric harvester	50 × 50 × 3.3 mm ³	1.3 μW	–	2022	Karalis et al. [221]
CFRP structural supercapacitor	250 × 40 × 2.9 mm ³	–	88 mF/g	2018	Senokos et al. [226]
CFRP structural supercapacitor	80 × 90 × 10 mm ³	–	101.6 mF/g	2019	Reece et al. [227]
CFRP structural supercapacitor	54 × 10 × 3.2 mm ³	–	30.7 mF/cm ²	2021	Sha et al. [228]

with a longitudinal modulus of 100 GPa. Energy was harvested through mechanical deformations exploiting the piezo-electrochemical transducer (PECT) effect in lithiated modified CF reinforcements. The PECT effect creates a voltage difference between the two CF laminae, generating a current when deformed with a specific power output of 18 nW/g.

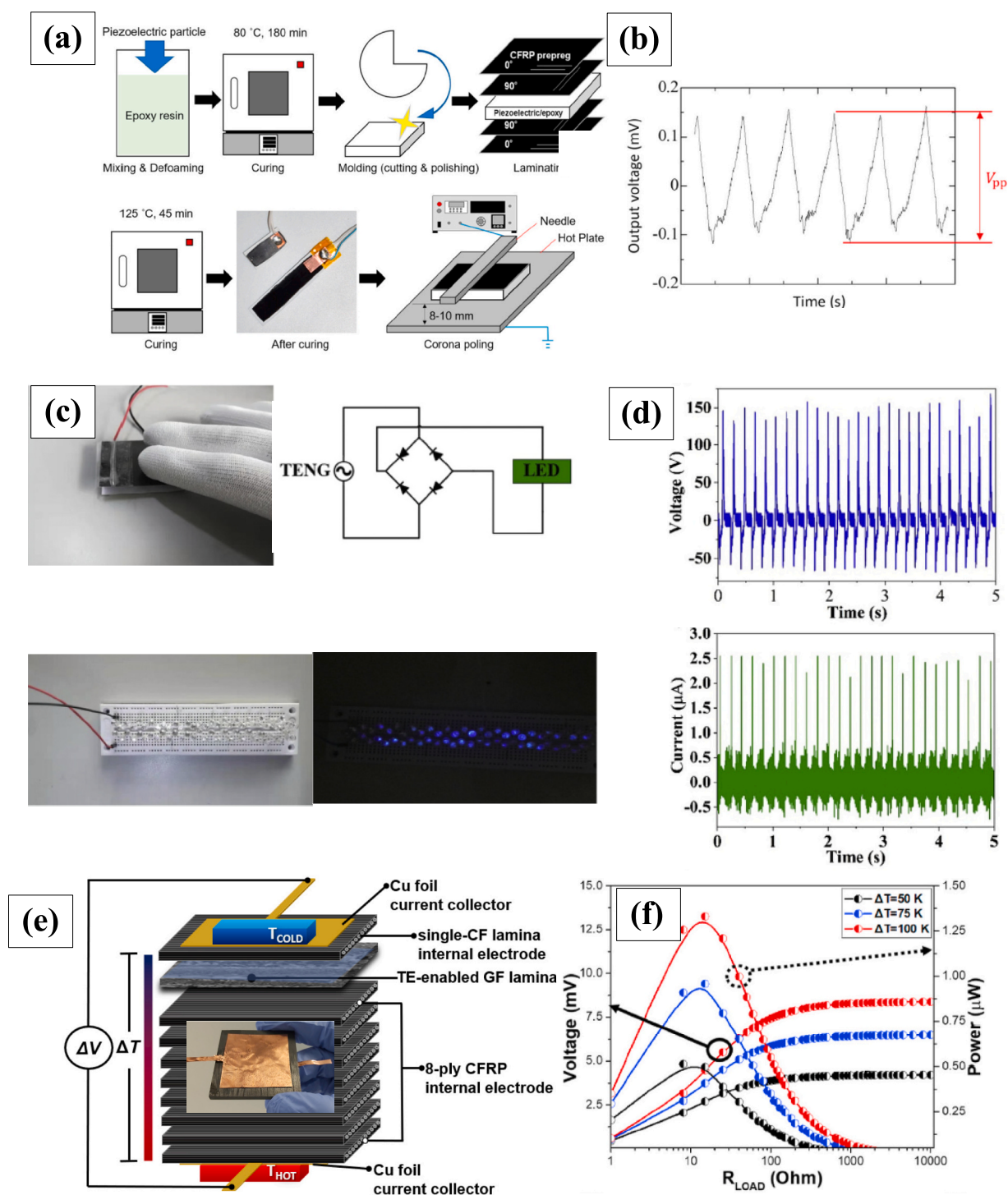
Another interesting energy harvesting phenomenon is based on triboelectrification. Triboelectric nanogenerators (TENGs) harness the contact-induced electrostatic potential generated across the surfaces of two dissimilar materials and convert waste mechanical energy into usable electrical energy, allowing easy flow of charges [213–217]. Bowen et al. presented an arch-shaped hybrid CFRP composite operating as a triboelectric device, which utilized a curved upper Cu electrode and a flat lower polyimide substrate, both of which were embedded within the CFRP structure. This device can be exploited as a triboelectric energy harvester exhibiting a generated voltage up to 300 mV [218]. Liu et al. [219] demonstrated a novel TENG and displacement sensor, consisting of the CFRP laminae and commercial office paper. The CFRP composite utilized as triboelectric active material and another Cu foil on paper acted as conductive electrode to study the mechanism and performance after identifying a triboelectric response. The peak output of open circuit voltage and short circuit current arose from finger motion (see Fig. 16c–d) reached 150 V and 2.5 μA, respectively resulting in a power of 8.36 μW. Additionally, two CFRP components were combined with paper gratings to fabricate a displacement sensor, where a self-powered function could be achieved for smart structural health monitoring purposes.

Waste heat recovery is a promising route toward the transformation from a fossil fuel-dependent era to a low-carbon society. Thermoelectric (TE) energy conversion relies on the Seebeck effect, relates temperature differences (ΔT) to induced electrical voltage (ΔV). Thermoelectric generators (TEGs) can harvest the ambient low-grade thermal energy losses to provide practical, fully energy-autonomous solutions for a wide application range [204], which require a power supply from micro Watts up to several hundreds of Watts scale. TEG devices consist of multiple interconnected thermoelements, either single-type or p–/n-type interconnected electrically in series and thermally in parallel, as lately demonstrated for a CFRP structural demo [220]. In more detail, the fabrication of the CF-based TEG and manufacturing of TEG-enabled CFRP involved the utilization of ten CF tows as p-type thermocouples properly serially interconnected with Cu wires of 0.1 mm diameter via small droplets of Ag paste onto a Kapton foil substrate. Then, followed a vacuum bagging process for the integration of the CF-based TEG and the manufacturing of the in-plane TEG-enabled CFRP prototype. The CFRP-based TEG generated a total voltage output of 19.56 mV and a total maximum power output of ca. 0.9 μW, upon being exposed to an in-plane temperature difference of 75 K. Except for CF reinforcements superior specific properties, such as high specific strength and stiffness, are also attractive due to their excellent conductive properties. This has also encouraged their utilization as current collectors or counter electrodes upon electrochemical device fabrication. For instance, a TE-enabled coated glass fibre (GF) functional ply based on a Tellurium nanowires (NWs)-PEDOT:PSS developed paste was purposely laminated to create a CFRP through-thickness TEG [221]. Simultaneously, the highly conductive CF reinforcing phases served as the outer electrodes for the structural device. The produced unidirectional (UD) composite

laminates generated a TE voltage of 8.4 mV and a TE current of 597.4 μA for 100 K through-thickness temperature difference i.e., a maximum power of 1.3 μW, as presented in Fig. 16e–f. The responsive temperature sensing capability of the TEG-enabled CFRP composite was also demonstrated, while three-point bending tests revealed a slight decrease in flexural properties due to the integration of the TEG functionality for the UD lamination.

Furthermore, the interest in the development of structural supercapacitors and batteries has been highly increased. Electrochemical Double Layer Capacitors (EDLCs) or supercapacitors are devices that present higher energy density than electrolytic capacitors and higher specific power than rechargeable batteries [222]. Typical supercapacitors consist of two electrodes and a dielectric layer as a separator in between, all embedded in an electrolyte. A crucial factor for their energy storage properties is the high surface area of the electrodes, as well as the ionic conductivity of the electrolyte [223]. Sasikumar et al. [224] modified the carbon fibre reinforced polycarbonate with a simple air spray deposition method of MWCNT, and found both enhanced mechanical and electrochemical performances. It was found that the symmetric pouch-type supercapacitor developed from the modified carbon fibre had an areal energy density of 102 μWh/cm² and an areal power density of 2.96 mW/cm² at 1.5 mA/cm².

Structural supercapacitors based on CFRP can be produced using carbon fibre laminae as electrodes to make use of their mechanical properties and electric conductivity, glass fibre can be used as a separator and modified polymeric resins as a solid electrolyte [225]. So far, most studies focus on using conductive CF as active material and a solid polymer electrolyte as a structural matrix, envisioning the employment of CFRP components as supercapacitors for the development of electric vehicles' body shell which could store a reasonable amount of electric energy. Senokos et al. [226] demonstrated a method to produce structural composites capable of energy storage by integrating CNT fibre veils interleaves and an ionic liquid-based polymer electrolyte as thin sandwich structures between carbon fibre reinforcing laminae, as shown in Fig. 17a–b. The resulting multifunctional CFRP acted both as a structural composite and an EDLC with a flexural modulus of 60 GPa and a flexural strength of 153 MPa, coupled with 88 mF/g specific capacitance and a power density of 37.5 mW·h/kg. Smith and colleagues [227] reported the manufacturing of a structural supercapacitor with activated carbon fabric electrodes and a solid composite electrolyte, consisting of an organic liquid electrolyte and an epoxy matrix, examined in different liquid electrolyte to epoxy ratios. Vacuum-assisted resin transfer molding was performed for the impregnation of the electrolyte mixture within the EDLC assembly. The optimum electrochemical performance was exhibited by the 1:2 w/w liquid electrolyte to epoxy composition, presenting a maximum electrode specific capacitance of 101.6 mF/g with a flexural modulus and strength of 0.3 GPa and 29.1 MPa, respectively. Wang and collaborators [228] developed a technique to fabricate CF electrodes modified with vertical graphene (VG) and manganese dioxide (MnO₂). The results indicated that the combination of VG and MnO₂ creates a significant synergistic effect in increasing the areal capacitance of the electrodes, as depicted in Fig. 17c–d. This synergistic effect is attributed to the dual effects of VG in increasing effective surface area and the electrical conductivity, which enable a better distribution of MnO₂ coupled a highly conductive network. A structural



supercapacitor demo based on the CF/VG/MnO₂ hybrid electrode, and a polymer electrolyte exhibited an energy storage capability of 30.7 mF/cm² and power density of 2210.3 mW/kg with a tensile strength of 86 MPa and a flexural strength of 32 MPa. Artigas-Arnaudas et al. [229] investigated the influence of surface treatment on the electrochemical performance of a CFRP supercapacitor. Electrodes were prepared by deposition of graphene nanoplatelets (GNPs) combined with PVDF and PVA binders onto the surface of a carbon fibre laminate. The optimized

8. Challenges and limitations

To realize the above-mentioned smart properties, the production of

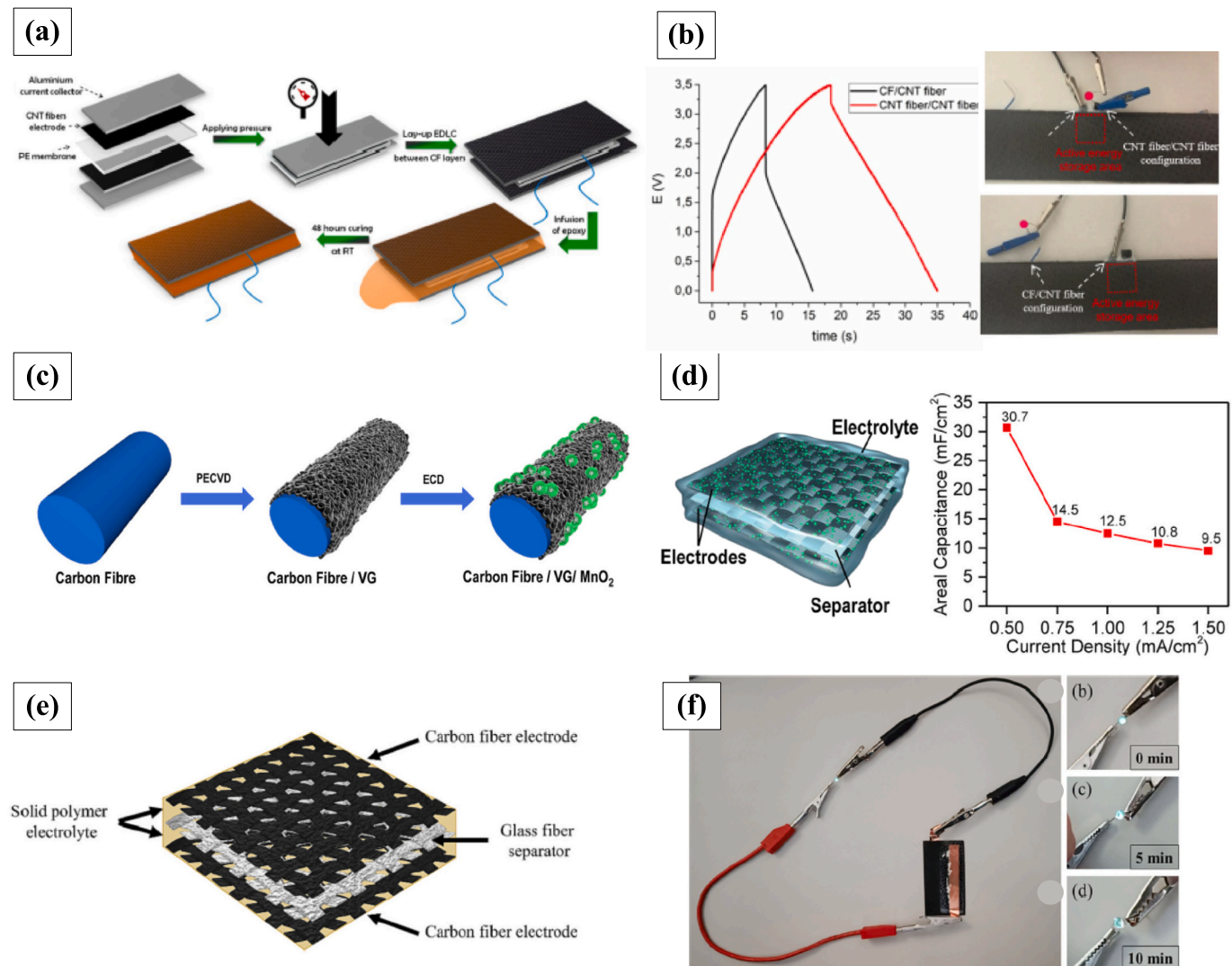


Fig. 17. (a) and (b) schematic description of the structural CFRP-based supercapacitor manufacturing process and snapshots of the real multifunctional structure during charging-discharging cycles. Reproduced with permission [226]; (c) and (d) production illustration of modified carbon fibre electrodes and the electrochemical testing of the proposed structural supercapacitor Reproduced with permission [228]; (e) and (f) schematic depiction of the multifunctional CFRP configuration and captures of the structural supercapacitor upon powering a commercial LED. Reproduced with permission [229].

CFRP and its installation in structures should be carefully considered. Some of the main challenges and limitations regarding the application of functional CFRP composites are listed below:

(1) CFRP should possess excellent electrical conductivity and the carbon fibres should be continuous without breaks. Defined doping or physical-chemical modification approaches might be applied to tailor the electrically conductive properties of the used CFs.

(2) Connecting CFRP composite to civil structural components can be difficult, especially when joining them with other materials such as concrete, asphalt, steel reinforcement, and wood. Ensuring strong and durable bonds between CFRP parts and other structural elements is essential for overall performance.

(3) To replace steel reinforcements, CFRP with defined surface properties and profiles needs to be produced in order to increase the bonding properties to the concrete matrix [177,230]. In addition, the specific shapes and thickness of CFRP need to be prefabricated when it is applied for the EMI shielding or deicing components.

(4) The manufacturing processes for CFRP composites are intricate and require specialized equipment and skilled labor. For practical application, a well-trained workforce regarding the installation and connection of CFRP to structures is needed, rather than the general labor

force.

(5) Thermal expansion of polymer matrix under high temperature can significantly degrade the mechanical strengths, let alone the electrical and multifunctional properties. It was reported that the bonding behaviors between polymer bars to concrete could be considerably reduced in seawater in a temperature of 80 °C [231]. In the fire situation, the thermoplastic polymer composites possessing poor fire resistance could even melt and cause fatal damage to the concrete structures. Here, a usage of the recently developed MCF can be a promising solution to overcome this challenge [232–234].

(6) CFRP composites can experience degradation over time due to environmental factors such as UV radiation, moisture, and temperature fluctuations. Understanding long-term durability and aging effects is crucial for ensuring their reliability in various applications. CFRP performs better on the chloride resistance compared to the traditional steel reinforced concrete, but the resistance to other chemical attacks such as sulphate and acid should be further investigated. Also, other durability issues include aging, shrinkage and creep performances of smart CFRP should be mastered. Since during service life several stimuli may occur at the same time, a discrimination of different parameters or sources needs to be mastered.

(7) CFRP composites demonstrate anisotropic material behavior resulting from the directional alignment of carbon fibres. Effectively incorporating this anisotropy into component design while accounting for vulnerable orientations poses a significant engineering challenge. Moreover, the standardization of testing methods and performance criteria for functional CFRP composites is still an ongoing process. This lack of comprehensive standards can create uncertainty in the selection and design process for various applications.

(8) It is clear that an application of CFRP for e.g., monitoring of civil infrastructure may yield massive amounts of data. Here artificial Intelligence (AI) can be used, by applying machine or deep learning approaches for distinguishing e.g. critical ions and their respective concentrations.

(9) To achieve an electrical-based self-monitoring via CFRP, also certain power supplies and circuits should also be developed. The electrical stability of CFRP should be achieved with excellent repeatability and serviceability. Also, the calibration of the electrical signal is critical before the practical application. However, these problems are widely investigated in recent experimental research but rarely solved for engineering applications.

9. Conclusions

This review paper summarizes raw materials, influencing factors, smart self-sensing, EMI shielding, self-heating, and energy storage properties of continuous carbon fibre reinforced polymer composites (CFRP). Challenges and limitations of CFRP for multifunctional applications in real-world engineering have also been proposed. Some conclusions can be drawn as follows:

- (1) The epoxy resin is the most used polymer matrix for the preparation of CFRP, in comparison to PMMA, PDMS, PLA and other polymer matrices. Moreover, the different arrangements of continuous carbon fibres, interface decoration between fibres to matrix, and fibres modification can influence the electrical and functional properties of CFRP.
- (2) On the one hand, the environmental factors of temperature, humidity and corrosive atmosphere affect the electrical properties of CFRP, thus influencing the piezoresistivity and EMI shielding effectiveness. On the other hand, it can be deduced that the CFRP could work as sensors for temperature, humidity and even corrosion detection based on the changes of electrical property.
- (3) The investigations on compressive and impact forces monitoring of CFRP are significantly less than the tensile and flexural forces monitoring, since CFRP is rarely used for compression and impact loads in practical applications. The electrical changes of CFRP subjected to flexural test are changeable due to the coexistence of compression and tension areas. Besides, the damage detection of CFRP in fatigue tests can also be achieved.
- (4) The carbon fibres paralleling to the electric field perform better for EMI shielding than the counterparts perpendicular to the electric field. Application of conductive coatings on carbon fibres, conductive fillers, as well as the short carbon fibres in a polymer matrix can improve the EMI shielding efficiency.
- (5) The Joule heating of CFRP is efficient especially when the thin polymer film is pre-covered with electrical insulation films. The self-heating property can be applied for the defrosting and deicing of pavements, which might be a perfect alternative for traditional chemical or manual deicing methods. CFRP can act as a supercapacitor with the carbon fibre and polymer as electrodes and electrolyte, respectively.
- (6) In terms of challenges and limitations, the thermal stabilization of CFRP especially under high temperature should be solved. MCF represents a promising alternative to conventional CFRP. Future research on MCF should focus on enhancing interfacial bonding,

improving durability under harsh environments, and developing cost-effective, scalable manufacturing methods.

- (7) To fulfill the various functions, the quality of carbon fibres and the production of CFRP with high electrical conductivity should be considered, as well as the wireless system for the collection of electrical signals.

CRedit authorship contribution statement

Wenkui Dong: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **George Karalis:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Marco Liebscher:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Tianling Wang:** Writing – review & editing, Writing – original draft. **Pengfei Liu:** Writing – review & editing, Writing – original draft. **Wengui Li:** Writing – review & editing, Writing – original draft, Visualization. **Viktor Mechtcherine:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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