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Advances in carbon-fiber reinforced polymers and composites for sustainable concrete structures

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Abstract

Sustainable materials that are characterised with cost-effectiveness, high durability and low density are typically required in the civil engineering markets to survive unfavourable severe loading and harsh environmental circumstances. Because of this, new applications in building and construction works have made the use of sophisticated composite materials as reinforcing for a wide spectrum of building structures. Carbon fibre reinforced polymers (CFRP) which possess remarkable attributes like high specific strength, stiffness, and lightweight nature, have garnered significant interest in the repairing and reinforcement of concrete structures. Improving the intrinsic material qualities of any construction material, like CFRP, is the most straightforward approach to make it better. Many of the restrictions associated with using materials can be overcome once the qualities of CFRP can be improved. This review, therefore, gives a thorough summary of the features and applications of CFRP in different building structural parts, including concrete slabs, columns, beams among others. Different fabrication techniques and surface modifications of CFRP to provide insight into their capabilities and possible drawbacks are highlighted. Moreover, sustainability issues surrounding CFRP as well as their recycling potentials in the circular economy are discussed. We conclude by providing outlook and challenges regarding the usage of CFRP composites in civil engineering applications.

Keywords: Carbon-fibre reinforced polymers; Building; Construction; Sustainability; Circular economy

1. Introduction

Extreme load conditions can cause unintentional damage to structures and replacing them is a costly endeavour [1]. Because of this, structures are intended to withstand critical loading under challenging environmental circumstances as well as short-term dynamic stresses. For structures to meet the conditions of appropriate strength and high durability, strengthening, repairing, and retrofitting are therefore usually necessary. Because of this worry, many strategies have been used in various contexts, including fibre reinforced polymers. Carbon fibre-reinforced composites are an excellent substitute for a variety of materials because of their intriguing mix of qualities and obvious benefits [2].

Carbon fibre reinforced polymer CFRP) has become the preferred material in many different applications including building and construction field. Its remarkable strength-to-weight ratio is one of its main features, which makes it especially useful in myriads of applications especially where both strength and decreased weight are crucial [3]. In contrast to conventional metals, CFRP is renowned for its resistance to corrosion, offering strength and longevity in challenging conditions. Its mechanical qualities are also highly customizable, enabling engineers to adjust stiffness and strength in accordance with needs. Because of CFRP's design flexibility, complex and aerodynamic structures may be created, giving businesses in sectors like transportation and architecture a competitive advantage. In addition,

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exceptional fatigue resistance, controllable conductivity, good stability, and adaptability to a variety of environments make CFRP a highly adaptable material that meets the changing needs of modern engineering in a range of applications, from multifunctional composites to structural components and more [4].

Due to the artificial composite nature of CFRP, the material's properties can be tailored for a specific purpose by adjusting the polymer matrix selection, strength, directionality, and number of supporting fibres. The two biggest disadvantages are the excessive cost of fibre production and the poor throughput rates at which parts may be produced. It takes roughly a few minutes to insert the fibres into the mold, inject the polymer, and wait for the part to solidify [5].

The technical applications of conventional metal reinforcements are surpassed by the carbon fiber reinforced polymer's flexibility. Manufacturers must first create the carbon filament that is braided into sheets to create the carbon fibre component of the wrap. The polymer chains are aligned during the chemical and mechanical processes that create the carbon filament, giving the finished fabric the appropriate qualities. The fibre is then heat treated, a process called as carbonization, to remove any remaining non-carbon atoms from the filament [5]. The carbon filament is then spun into a continuous sheet, according on the finished sheet's required thickness, finish, and direction [6].

The appropriateness of CFRP composites for large-scale projects like building foundations and bridges is a key component in their utilization in civil engineering. CFRP composites are perfect for this application because bridges must withstand a range of loads and weather conditions, strengthening pre-existing structures. CFRP composites can extend the service life and weight carrying capability of steel and concrete structures by adding reinforcement[6].

Concrete infrastructures can also be exposed to a range of load types and risks since they are made to withstand several decades of usage and a variety of user types. As a result, studies were conducted to determine how well fibre reinforced polymer (FRP) strengthening systems performed under various stress scenarios, including as impact, explosion, fire, cyclic (fatigue/seismic), static (monotonic), and others. As a result, sophisticated FRP varieties with much better qualities and a wide range of applications have been developed. To sum up, it appears that the exploitation of CFRP composites in structural building elements will continue to expand[7,8].

In this review, numerous applications of carbon fibre-reinforced polymer (CFRP) composites in civil engineering are examined. It focuses on their use in structural building elements including beams, slabs, columns, shear walls, etc. To give a thorough grasp of CFRP composites' efficacy in circular economy, issues related to the recycling of CFRP, and sustainability benefits are discussed. Finally, challenges and future research opportunities are highlighted to identify the potential research gaps for researchers and engineers in this field.

2. Carbon-fibre reinforced polymers

Carbon fibre reinforced polymers are produced when carbon fibres are incorporated into polymer resins [9]. The polymer resin serves as a matrix to hold the carbon fibres in place while the carbon fibres serve as the reinforcement material. Fibers with a carbon content of at least 90% and up to 100% are referred to as carbon fibres. Some of the precursors for the polymer matrix include but are not limited to cellulose, pitch, polyacrylonitrile and polyvinyl chloride [10]. These precursors undergo a sequence of heat treatments and conditioning to become carbon fibres. When viewed in a larger context, carbon fibres are tiny filaments that are hardly perceptible to the human eye, measuring between 5 and 10 μm in diameter [11]. In a broader sense, carbon fibers are minuscule filaments with a diameter of 5 to 10 μm that are nearly invisible to the human eye. All carbon fibres have tensile strengths greater than those of steel materials, although having somewhat lower densities. One useful metric to demonstrate the great strength and lightweight nature of some materials is the breaking length.

Based on the thermal reactions of polymers, polymer resins employed in CFRP can be classified into thermoplastic and thermosetting resin [12]. Despite their identical names, thermoplastic and thermosetting resins differ greatly in their molecular makeup and behaviour. Thermoplastic resins are composed of polymers that are joined together either linearly or branched by van der Waals forces or intermolecular interactions[12]. The motion of molecular chains can only be somewhat restricted by this linear or branched molecular structure, which renders the thermoplastics tractable and remeltable when heat and pressure are applied after curing. CFRP is an example of an orthotropic material due to the variations in modulus and strength between the polymer resin and the carbon fibre. CFRP primarily displays the mechanical characteristics of carbon fibre in the fibre direction, namely a high modulus and comparatively high strength. However, CFRP primarily displays the mechanical characteristics of the polymer resin in the direction perpendicular to the fibre axis, namely, relatively low strength and low modulus. Because of its extreme orthotropy, CFRP cables are challenging to anchor [13].

In nature, carbon fibre is an anisotropic material that is produced at 1,300°C. This fibre's main benefits are that it is resistant to chemical effects, has a high elastic modulus, low density, low conductivity, high fatigue strength, good creep level, and does not absorb water as well [14]. Nevertheless, the weak points of carbon fibre include its low compressive strength and anisotropic (decreased radial strength) nature. Additionally, the comparatively high energy needed to create carbon fibre is seen to be a weak attribute that drives up costs [14,15].

Table 1 Some properties of carbon-fiber reinforced polymers [14,16]

Property	**Polyacrylic Nitrile Carbon**		**Pitch Carbon**	
	High Strength	**High Modulus**	**Ordinary**	**High Modulus**
Density (gm/cm^3)	1.7–1.8	1.8–2.0	1.6–1.7	1.9–2.1
Tensile Strength(MPa)	3430	2450–3920	764–980	2940–3430
Young Modulus (GPa)	196–235	343–637	37–39	392–784
Elongation (%)	1.3–1.8	0.4–0.8	2.1–2.5	0.4–1.5
Coefficient of Thermal Expansion (10^{-6}/°C)	−0.6 up to −0.2	−1.2 up to −0.1	−0.6 up to −0.2	−1.2 up to −0.1

3. Properties of CFRP

Many issues pertaining to the deterioration and reinforcement of infrastructure, such as buildings and bridges, have solutions offered by CFRP. By adding CFRP reinforcement, possible corrosion issues can be avoided, and the component's structural strength can be significantly increased. By utilizing carbon fibre-reinforced plastics effectively, the structure's lifespan can be greatly extended, reducing the need for maintenance [9]. Due to its many advantages, CFRP is a great material for public and commercial buildings. Among the feature of CFRP are:

- **High tensile strength**: CFRP can bear greater pressure without cracking because carbon fibres are more flexible than concrete or steel.
- **Fatigue resistance:** Because the material doesn't break down easily, using it in constructions requires less upkeep overall.
- **Strength against the elements**: CFRP is resistant to a wide range of harsh environmental factors, including high humidity, intense rain, and chemical exposure.
- **Light weight**: CFRP weighs less than several other building materials despite its higher price. It thus requires less labour because fewer people are needed for installation, which lowers labour costs and transportation expenses [17].

CFRPs are produced in a variety of formats and can have their properties and modes customized for a range of uses [18]. The types of carbon fibres and resins used, the production processes, the fibre content, and the orientation all affect their qualities. Unidirectional carbon fibre reinforced epoxy plates, bars, and other products are frequently made by pultrusion and wet layup techniques. Carbon fibre (CF) is one the most common types of fibre reinforcements used in composite materials [18,19]. Others include glass fibre, aramid fibre, basalt fibre among others. CF has been utilized in sophisticated structures because of its exceptional mechanical qualities, including strength, modulus, and fatigue resistance. More than 92% of the composition of CF is made up of carbon components in amorphous, crystalline, or partially crystalline form. The crystalline form has the same crystal structure as graphite, which is made up of two-dimensionally arranged sp^2 hybridized carbon atoms in the shape of a honeycomb in the x-y plane. Two types of bonding are present between carbon atoms in a layer: (1) covalent bonds, which are formed by the overlap of sp^2 hybridized orbitals, and (2) metallic bonds, which are formed by the delocalization of p_z orbitals, or the π electrons [20] .

Through intricate carbonization procedures, pitch, rayon, and polyacrylonitrile (PAN) fibres are used to create most commercial carbon fibres today [21]. PAN-based carbon fibers account for 90% of the market for carbon fibre among those precursors. The density, conductive, and mechanical properties of carbon fibres are determined by the precursor and pyrolysis conditions, which introduce different microstructures inside the carbon fibers. The industry offers a wide range of carbon fibres based on their modulus and tensile strength [22].

Most carbon fibers utilized in CFRP used in construction today are standard modulus (HT) carbon fibres, which have tensile strengths and tensile moduli ranging from 2.5 to 300 GPa, respectively [21]. Additionally, high modulus CFRPs related to CF are utilized in construction, for example, to reinforce steel structures[23]. Their widespread acceptance is negatively impacted by their substantially greater price. Furthermore, except for breaking strain, carbon fibres are far superior to their counterparts, namely glass and basalt fibres, based only on mechanical feature [24].

A low concentration of acid, alkaline, and other often encountered aqueous solutions are just a few of the typical substances that carbon fibre demonstrates good resistance to because of its inertness [25]. Benmokrane and co-workers conducted research recently whereby they examined the chemical resistance of carbon, glass, and basalt fibres [26]. The fibres were immersed in 10% HCl, saline solution, and distilled H_2O to assess weight loss, surface shape, and compositional. Carbon fibre only exhibits minor changes in mechanical characteristics and microstructures, whereas glass and basalt fibres deteriorate considerably because of ion exchange in acidic solutions and fracture of the Si-O-skeleton in alkaline solutions. The inert carbon fibre can be activated by strong acids, such as nitric acid, which can oxidize the carbon fibre surface and generate –OH, –COOH groups. This strengthens the connection between polymer matrix and carbon fibre. Thus, carbon fibres have already been treated with severe acid treatment [26].

However, oxidation makes carbon fibre vulnerable to elevated temperatures in the air. Modulus and tensile strength of a PAN-based carbon fibre begin to decline after 30 minutes of air exposure to 400 °C. The exposure temperature decreases significantly when the CF diameter begins to decrease after 30 minutes in air at 500 °C. After 30 minutes of heat treatment at 600 °C, only 50% retention is achieved. In contrast, carbon fibres do not oxidize in an inert atmosphere, and following the heat treatment, there is very little mass loss. Heat treatment modifies the carbon fibre's microstructure and, consequently, its mechanical characteristics [27].

Resistance (shear or compression), lateral force, and durability of the composite material are all significantly impacted by the polymer matrix [7]. An organic polymer, the resin often has a spectrum of melting or softening reactions when heated. Under the influence of outside influences, it tends to distort when softening[28]. It is either a solid, semi-solid, or occasionally liquid at ambient temperature. Epoxy, vinyl ester, polyurethane and phenolic resins are examples of commonly used polymer matrices. The sizing agents of commonly used carbon fibres are specifically made for epoxy resins, which contributes to the widespread usage of epoxy in addition to its good thermo-mechanical characteristics, processability, and availability. Certain novel matrices with intriguing qualities have been studied recently, including vinyl ester and polyurethane. It is important to remember that the epoxy system is a member of a large family that offers countless combinations of hardeners and epoxy resin. Additionally, some additives can be used in formulation. The epoxy resin technique typically used for cables, plates and other items is based on pultrusion of bisphenol A with anhydride hardeners. The resin hardener often selects a room temperature curable resin, like polyamide, for wet layups of CFRPs. Other high-performance polymers, like nylon, thermoplastic polypropylene, and thermosetting polyurethane, have been utilized in civil engineering recently [28].

4. Fabrication techniques

Two primary techniques are used in the fabrication of CFRP: additive manufacturing and traditional manufacturing [29,30]. In traditional production, the procedure usually starts with the orientation-specific layup of carbon fiber sheets that have been impregnated with a polymer resin, like epoxy. A robust and lightweight composite material is produced by curing this layup in a controlled setting. In businesses where control and precision are crucial, the conventional technique is well-established and frequently utilized. However, 3D printing, also known as additive manufacturing, has become a cutting-edge method for fabricating CFRP [31]. Using a digital design as a guide, layers of CFRP are progressively constructed in this manner. Increased personalization, less material waste, and more complicated designs are all made possible by additive manufacturing. The choice between the various methods is contingent upon various criteria, including production volume, part convolution, and the desired qualities of the final CFRP product. Each method possesses pros and cons.

4.1. Plasma-assisted mechanochemistry method

One notable feature of the plasma-assisted mechanochemistry (PMC) method is its capacity to form covalent connections in the solid state between nanofillers and polymers, which guarantees good processability and preserves environmental friendliness and cost-effectiveness [32,33]. Polymers and carbon fillers are joined chemically and physically by plasma treatment and mechanical force. In order to improve the interfacial area and ease mechanical interlocking, CNTs are strategically employed as bridging materials. As a result, the PMC-treated CFRPs show an enhanced degree of entanglement, a decreased C-factor, and effective stress transfer from the polymer to the filler [34]. Furthermore, the PMC method significantly enhances the mechanical properties of CFRPs even at low carbon fibre loading levels. The PMC-treated CFRPs exhibit a unique pattern of continuous improvement in tensile strength, Young's modulus, and elongation at break with increasing CF content up to 30 wt%. Consequently, with a 30 weight percent CF content, the PMC-treated composites show noteworthy improvements of 47.1% in tensile strength, 43.0% in Young's modulus, and 91.7% in elongation at break in comparison to conventional composites [34]. Carbon nanotubes were inserted at the PK/CF interface after polyketone (PK) and carbon fibers (CFs) were mixed utilizing PMC processing with O_2, N_2, and Ar plasmas (Fig. 1). In comparison to conventional composites, the resultant PK/CNT/CF composites showed markedly better mechanical properties, especially following O^2 and N_2 plasma treatments, showing a noticeable 31% increase in Young's modulus and a substantial 20% increase in tensile strength [34].

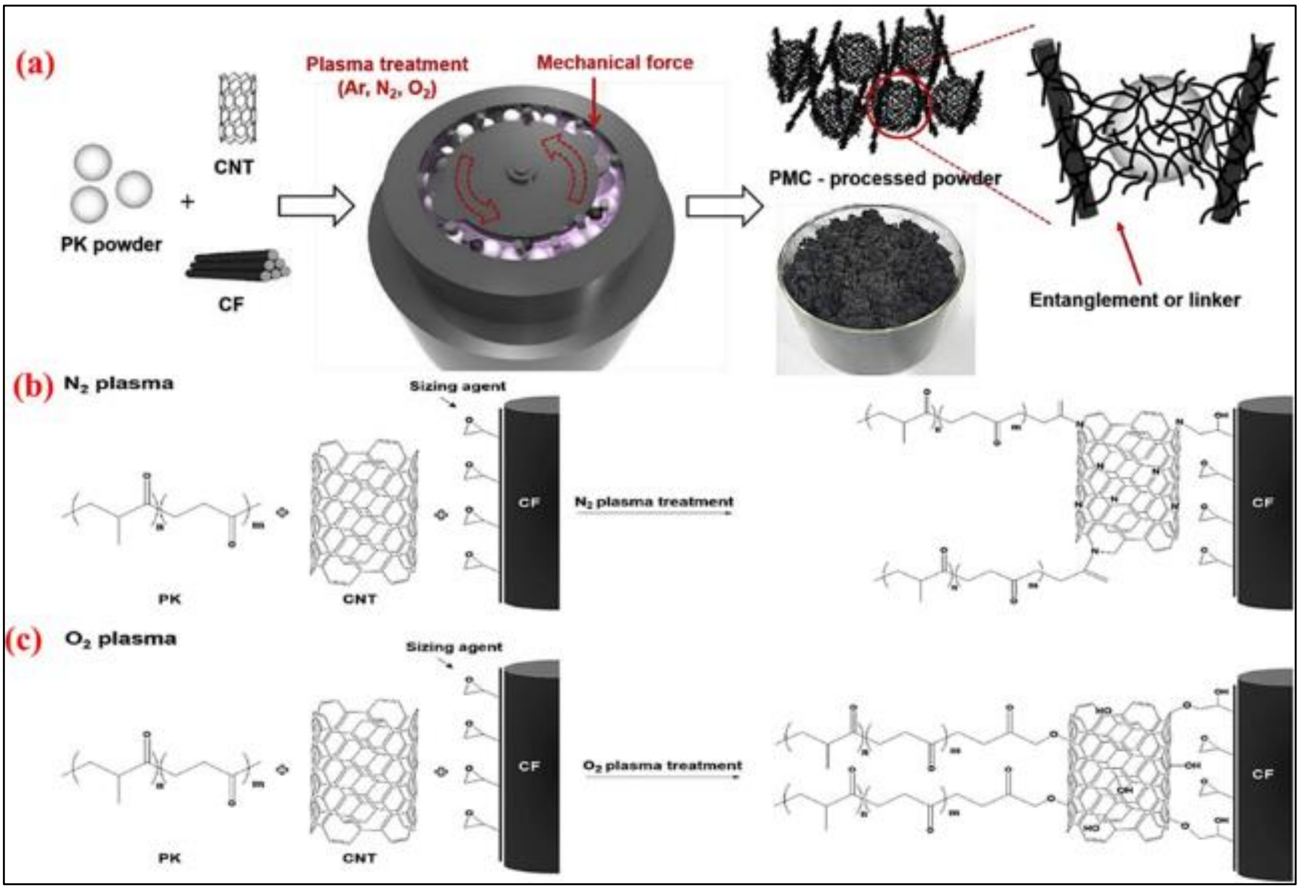

Figure 1 Diagrammatic representation of the PMC synthesis of PK/CNT/CF composites, (b–c) Diagram showing how PK, CNT, and CF are exposed to N and O plasma [34]

4.2. Vacuum infusion method

A cutting-edge method used in the production of composites; the vacuum infusion process (VIP) uses vacuum pressure to make it easier for resin to infuse into a laminate structure [35]. Using this technique, a mold is carefully filled with dry materials, like carbon fibres. The system is then subjected to a vacuum before the resin is added. The most important part of this procedure is creating a full vacuum, which is done by strategically placing tubing to start a suction effect. The resin is pulled into the laminate after the vacuum is created, guaranteeing that the dry materials are completely impregnated with the liquid resin. This method is particularly well-suited for large constructions where structural integrity is crucial because it produces CFRP components with high fibre content, reduced voids, and improved mechanical qualities. Reducing injection time without sacrificing mechanical qualities improves the vacuum infusion process for large-scale constructions when binder is used in small quantities and the resin intake port number is optimized .

The most popular vacuum infusion method, the seemann composites resin Infusion molding Process (SCRIMP), results in composites with lower-than-desired fibre volume fractions and significant thickness fluctuations. Moreover, thorough experimental evaluations of popular vacuum infusion methods showed that no method performed better than any other in terms of all important variables, including void content and fibre volume percentage. Furthermore, process automation can lower the high human costs and high inherent material and process variabilities associated with vacuum infusion methods. Consequently, process automation and additional enhancements to current vacuum infusion techniques may considerably and continuously improve product quality while lowering material and process variabilities, leading to a reliable production process for premium fibre-reinforced composites [36].

Process automation as shown in Fig. 2 lowers material and process variabilities, improving the quality of the vacuum infusion process's output. Additionally, process automation enables the vacuum infusion process to be optimized using techniques like machine learning and numerical simulation [37].

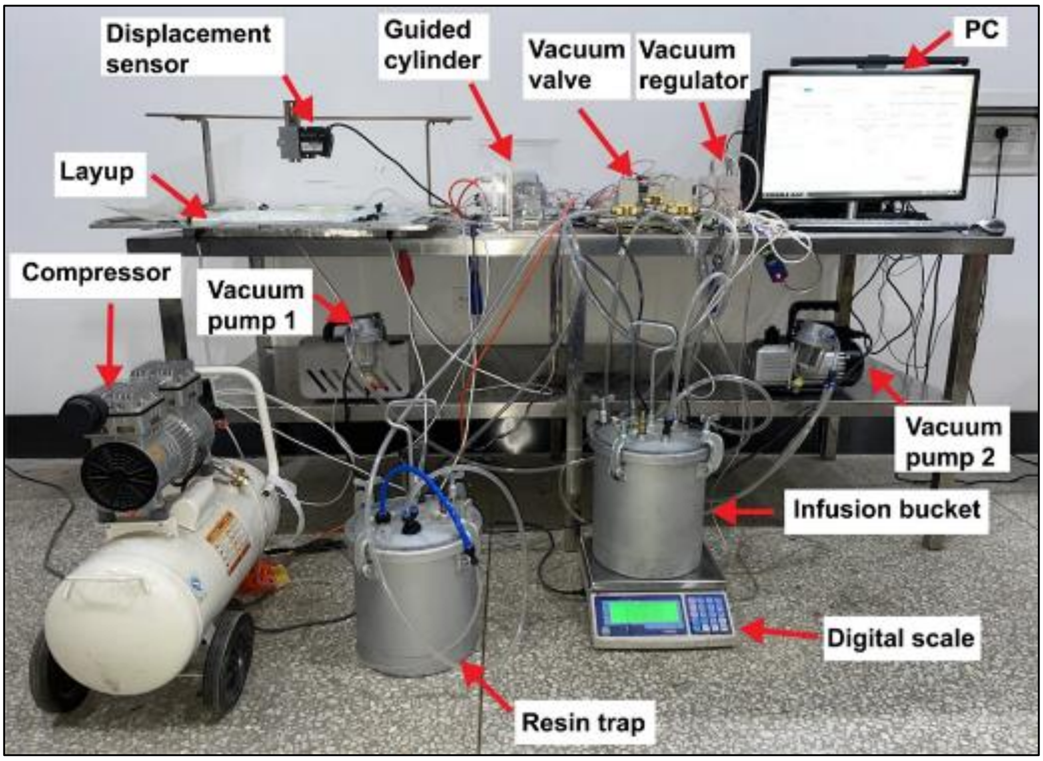

Figure 2 The workstation showing automated vacuum infusion [37]

4.3. Selective laser sintering

Because they can be designed without molds, CFRP made by selective laser sintering (SLS) have a great deal of potential for a variety of applications [38]. Short carbon fibres are added for reinforcement when powdered matrix materials are sintered using a laser in SLS. One important benefit of SLS over other additive manufacturing processes like SLA, FDM, and material jetting is that it doesn't require any support structures. SLS offers greater cost-effectiveness and manufacturing efficiency since it lacks support structures. One of the issues introduced by SLS's rapid cooling feature is the possibility of deformation, shrinkage, and warping in the printed items[39]. Despite the SLS technique's seeming simplicity, several intricate physical phenomena are involved in the process: powder spreading, the interaction between the powder bed and the laser beam, melting of the polymer, the coalescence of the fused powder and its densification, polymer crystallization, and shrinkage [40]. These events also occur on a variety of temporal and spatial scales. For instance, several factors pertaining to the laser's interaction with the powder bed, the melting process of the polymer, and the evolution of the thermophysical characteristics of the melting pools are crucial in establishing the density and microstructure of the finished products, even after accounting for the energy input provided by the laser or "melting" substep [41,42].

5. Interfacial modifications of CFRP

Carbon fibre surface changes have found widespread application in carbon fibre-based material disciplines as a means of improving fibre performance and reinforcement of resulting composites [43]. Oxidation and non-oxidation are the two categories into which the modification techniques fall. The process of oxidation involves using an oxidizing chemical to increase the activity of functional groups on the surface of carbon fibres. increasing the oxidation-induced physical and chemical interactions between the fibres and resin to enhance the composite materials' interface performance [44].

The process known as non-oxidation can be used to increase the resin's penetration and interfacial reactivity with the carbon fibre, hence enhancing the composite materials' interfacial performance. Through coating, grafting, cleaning, etching, and other processes, the carbon fibre surface's structure, and surface energy were controlled. These techniques, which include surface cleaning, chemical grafting, and plasma, can help to increase the interface's engagement and surface roughness while partially removing the weak layer of the carbon fibre interface. In the meantime, the carbon fibre’s surface energy will rise, improving the interface infiltration effect. To encourage interfacial reactions, the functional moieties on the surface of the fibres will grow [44].

5.1. Supercritical or subcritical fluids cleaning

Supercritical H_2O, acetone, and subcritical aqueous KOH solution can all be used to clean carbon fibres. Supercritical fluid possesses qualities of a liquid and a gas, including good heat transfer, high diffusivity, and density between the two states [45]. Supercritical fluid is a medium with exceptional transport properties from this perspective. Research has revealed that the use of these three fluids as processing mediums produced a superior cleaning outcome than the conventional method of Soxhlet extraction with acetone. The influence of cleaning temperature and duration time was also explored [46]. Furthermore, Soxhlet extraction with acetone is less effective than employing supercritical acetone or subcritical aqueous KOH as a cleaning medium [47].

The oxidation treatment of carbon fibres involved the use of supercritical H_2O and H_2O_2 as an oxidation medium to enhance the interfacial characteristics between the carbon fibres and polymer matrix. Because of treatment, the experiment's findings demonstrated that carbon fibre surfaces had a greater quantity of oxygen functional groups, most of which were carboxyls. Concurrently, the oxidation process in supercritical H_2O had a major impact on the treated carbon fibres’ surface appearance [48].

5.2. Anodization

Most carbon fibres are utilized as reinforcement in resin matrix, so to obtain adequate adhesion between the fibres and resins, their surfaces must be oxidized. Anodization is the most practical surface treatment for commercial carbon fibre manufacture because it is easy to control the degree of surface oxidation [49,50]. Three distinct reaction mechanisms coexist during the anodic oxidation of carbon materials in aqueous electrolyte solutions. These mechanisms include intercalation reactions, degradation of the carbon material, and the formation of covalently bonded surface groups. The electrolyte system's type, concentration, and electrolysis conditions all had an impact on the reaction mechanism. Numerous studies have documented modifications to the surface structures of carbon fibres because of the anodic oxidation process [51].

Cheng et al. [52]carried out anodizing surface treatment to modify the aluminium substrate and achieve optimal channels by varying the electrolytes in an etchant solution. As previously noted, CNTs are guided into the micro-channels on the surface of the Al substrate using the basic RPC technique. In the meantime, to guarantee a stronger interaction between CFRP and the epoxy resin, surface sanding and RPC are also applied to CFRP. Single lap shear tests are used to quantify bond strengths and identify changes in failure modes with varying surface treatment techniques. The surface morphology, roughness, and wettability of the micro-porous oxide coatings on the Al substrate surface are other significant attributes that are also studied before and after the surface treatments [52]. By using a direct adhesive bond, the approach reduced the amount of subsurface void defects and increased the shear strength of the bonded composite. The latter encourages efficient interface behaviours through RPC, such as expanding contact area, decreasing void defect, and enhancing mechanical occlusion. Al substrates underwent pre-treatment, as shown in Fig. 3a, prior to anodizing. Next, following pre-treatment, as seen in Fig. 3b [52].

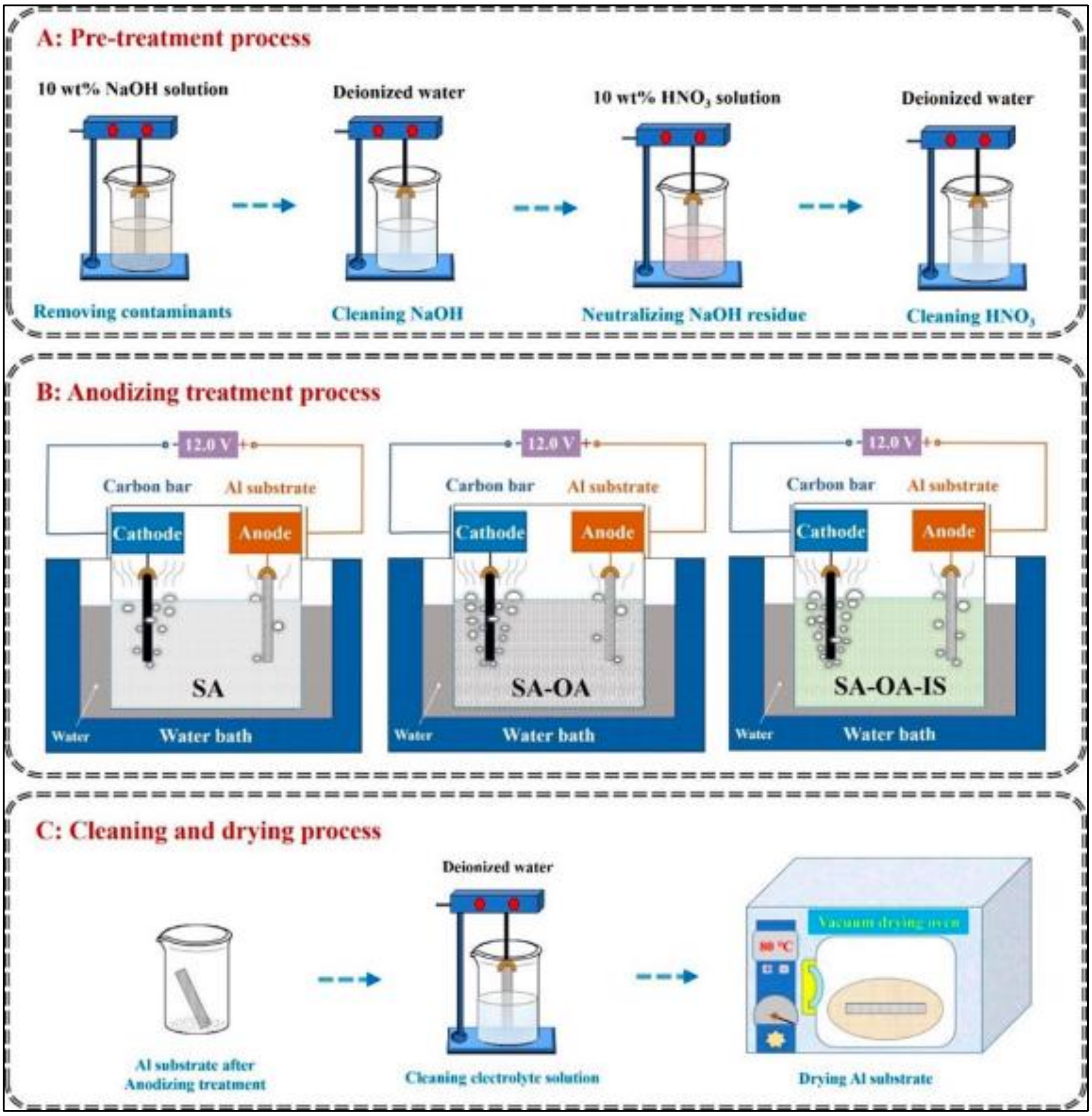

Figure 3 The three electrolyte solutions used in the pre-treatment and anodizing procedure to form vertical micro-channels on the surface of the aluminium substrate [52]

5.3. Plasma and irradiation method

Carbon fibre surfaces are regularly modified by plasma treatment to enhance the fibre's adherence to the polymer matrix [53]. These days, a wide range of industrial applications use plasma modification to improve bonding and adhesion in polymer matrices. Numerous research has so far documented modifications to the surface structure of fibres by plasma treatment [33]. For instance, Qiu et al. treated the carbon fibre surface with He/O_2 plasma to study the interface performance. They found that the fibre surfaces may become rougher because of the plasma treatments. Additionally, as treatment time rose, the carbon fibres' dynamic water contact angles shrank. They claimed that this was the primary factor raising the IFSS between PI and carbon fibre [54].

Gamma radiation is a type of electromagnetic radiation that has a high energy per photon and an exceptionally high frequency. Without the need for a catalyst, radiation can cause a chemical reaction in the solid, liquid, or gas phase at any temperature. It is a risk-free way for individuals to save energy, lower maintenance costs, and safeguard the environment from pollution. Furthermore, γ-rays have a high penetration depth into a wide range of objects and can, through the thickness of the irradiated materials, produce a uniform distribution of radical initiating sites without taking volume or shape into account, which is advantageous for the industrialization of CF [55].

5.4. Carbon nanotube

Because of their high mechanical qualities and comparable composition to carbon fibres, carbon nanotubes (CNTs) have been utilized to change the surface of carbon fibres. Many techniques have been established to date, including chemical grafting of CNTs onto the functionalized fibres, coating fibre surfaces with sizing containing CNTs, chemical vapor deposition |(CVD), and electrophoretic deposition. Over the past 20 years, these technologies have been discussed extensively[56]. According to Wang et al., if the thickness of the catalyst coating and the CVD conditions are appropriately managed, growing CNTs on the surface of carbon fibre can simultaneously improve its tensile strength and interfacial characteristics. They found that some of the damage caused by catalyst nanoparticle synthesis, carbon crystal enlargement, and the creation of crosslinks between nearby crystals by CNT through CVD can be repaired by grafting CNTs on carbon fibre surfaces [57].

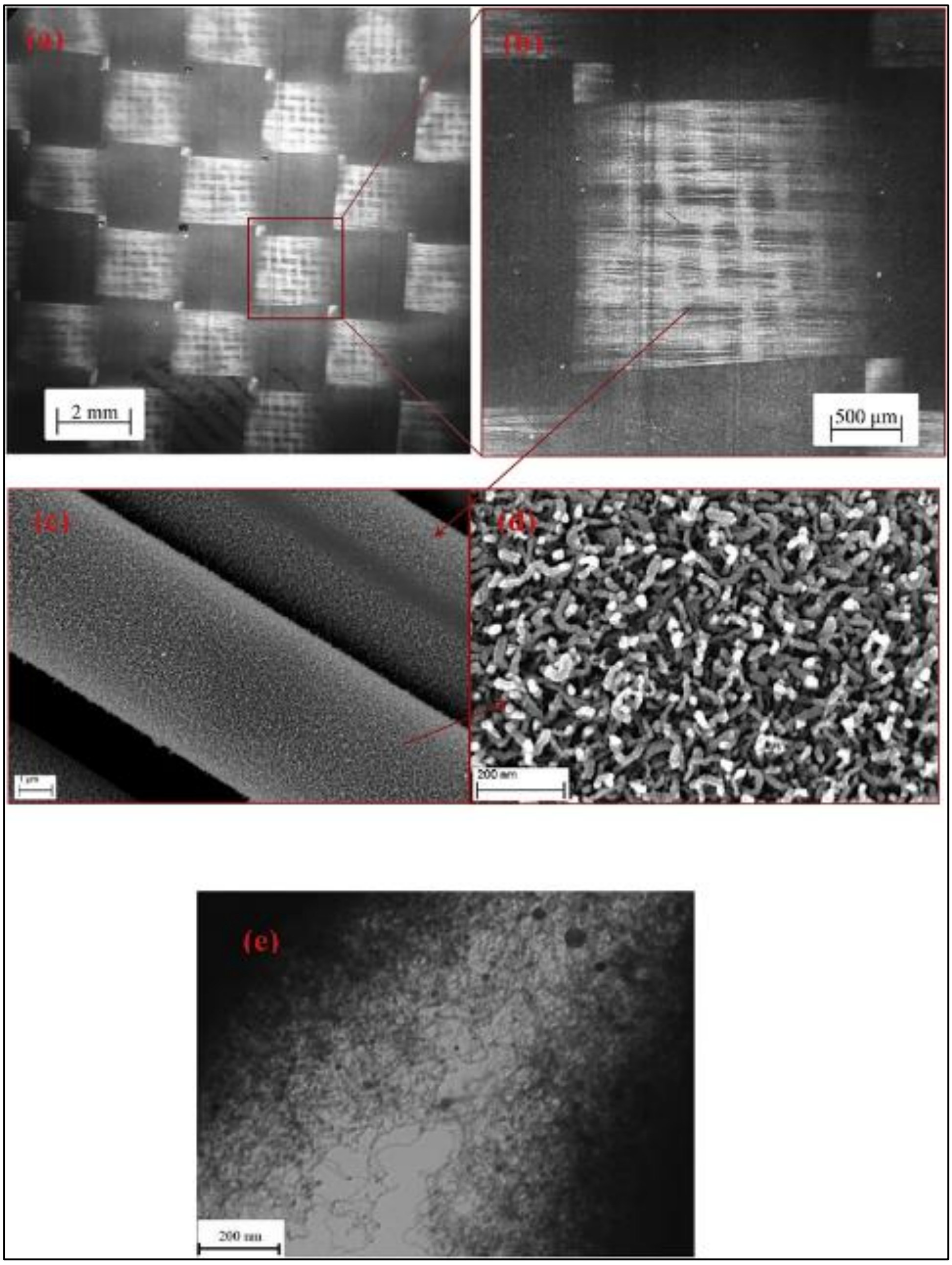

Figure 4 a. Microscopic image of the patterned growth over a woven carbon fibre fabric, (b) a magnified view of the patterned growth over a single fibre strand, (c) SEM image of the MWCNT growth over a single fibre, (d) a magnified image of the MWCNT forest grown over a carbon fibre, and (e) a TEM micrograph of the surface grown MWCNTs are all examples of the GSD method of MWCNT growth [59]

Recently, a novel approach has been devised that adds a highly reactive nano-component on the surface of carbon nanotubes (CNTs) or between fibres and CNTs. It improves wettability and forms strong chemical bonds at the interphase in addition to utilizing the mechanical improvement of carbon nanotubes (CNTs) to increase composite interlaminar strength. For instance, amine functionalized CNTs can significantly enhance the wettability and surface reactivity of carbon fibre as well as the overall performance of composites when grafted onto the surface of octaglycidyldimethylsilyl POSS modified carbon fibre. This tactic allows for the formation of interphase with diverse complex nanostructures, which optimizes material performance in accordance with a range of needs [58].

Boroujeni et al. [59]employed surface grown MWCNTs to produce CFRPs which were then subjected to monotonic tensile testing. To find out how different surface grown MWCNT topologies affected the fatigue damage progression and CFRP life, the resulting composites were also subjected to tension-tension fatigue loading at three stress levels: 85, 90, and 95% of their monotonic strength using a cyclic stress ratio of 0.10. The fatigue life of the CFRPs with patterned growth of MWCNTs shown a noteworthy 150% improvement in fatigue life, according to the results [59]. The fractography investigation clarified how MWCNTs shield the fibre yarn from matrix cracks, resulting in a notable increase in fatigue life. The images of MWCNT growth for a patterned GSD MWCNT grown (PG) sample configuration is displayed in Fig. 4(a) on a woven carbon fibre fabric. An enlarged FE-SEM image of MWCNT development over a single carbon fibre is shown in Fig. 4(c). A higher magnification micrograph of the developed MWCNTs is presented in Fig. 4(d), which demonstrates their wavy forms and approximate diameters of 20 nm [59].

6. Applications

Of all the known fibre-reinforced polymers, carbon fiber reinforced polymer (CFRP) is arguably one of the most appropriate for enhancing the strength of structures. Numerous prior studies demonstrate that the bonding of CFRP with steel sections greatly increases both flexural strength and fatigue load carrying capacity [60]. CFRP is favoured for reinforcing steel or concrete structures because of its low density, high strength to weight ratio, and corrosion resistance. High modulus (HM) CFRP can also be employed because it has three times the modulus of elasticity of steel [61]. Pultrusion is used to manufacture the CFRP plates, and epoxy adhesive is used to bind them to steel. Before applying it to the steel, the surface is first roughened up by grit blasting to remove any rust pits. Acetone is then applied to remove any remaining impurities. The proper methods for applying, installing, and designing HM CFRP to strengthen steel-concrete girders.

Setunge et al. described the various techniques for strengthening, the kinds of FRP that are utilized, and the factors that are taken into account [62]. Four specimens were examined by Taljsten et al., three of which were rectangular beams strengthened with CFRP and one serving as a reference [63]. It was concluded that CFRP installed close to the surface has a higher load carrying capacity. Issa and colleagues [64]employed two distinct CFRP materials, Sika Wrap HEX 230C and Sika Carbodur increase flexural strength, and it was observed that strength and load bearing capacity are increased when CFRP is bonded to the concrete structures. Zhang et al [65] showed that it was possible to create a composite beam out of ordinary concrete (OC), steel fiber reinforced concrete (SFRC), and CFRP. The overall stiffness and bearing capacity of beams strengthened with CFRP plates were enhanced. Nonetheless, the CFRP plates altered the beam's mode of failure. When the CFRP panels fail, the bearing capacity of the beam also approaches its limit, it falls, and cracks appear and spread quickly. Applications of CFRP in concrete structures are given below [65].

6.1. Reinforced Concrete shear walls

Adding strength and stiffness to a building for lateral resistance is the primary purpose of a shear wall [66]. Shear walls are exceptionally strong and stiff in-plane, making them useful for both resisting gravity pressures and enormous horizontal stresses like wind or earthquake forces. For RC shear walls to prevent brittle shear failures, proper strength and ductility must be carefully considered during design. Throughout the world, there are several shear walls that have been damaged by earthquakes, by shoddy construction, or by inadequate design and craftsmanship [67].

According to Huang and co-workers [68], shear walls have been strengthened through the application of CFRP to enhance their strength and ductility. The CFRP strips were aligned vertically to the two faces of the shear walls in the study, strengthening them. The results demonstrated a significant improvement in the structural wall's secant stiffness and flexural capacity. FRP composites have been retrofitted onto RC walls by Sun et al to enhance the wall's ductility and seismic load capability. Bi-directional sheets were used to wrap the repaired walls in the wall region and uni-directional sheets on the border elements. The findings of the experiment demonstrated that shear walls' structural capacity could be improved under lateral loading and that the strip configurations had a significant impact on the behaviour of strengthened walls and failure modes [68].

Using CFRP composite laminates, Mosallam and Nasr [69]conducted an experimental study to examine the strengthening of reinforced concrete shear walls with apertures under cyclic lateral loading. The CFRP-strengthened wall specimens with central window openings (R-WO) and eccentric door openings (R-DO) had average peak loads that were 1.32 and 1.25 times higher, respectively, than the un-strengthened walls with window openings (C-WO) and door openings (C-DO), according to the experimental results. However, the results also demonstrated that the CFRP-reinforced wall with central window opening (R-WO) had the highest toughness and ductility of any wall specimen, and that the failure modes and performance of the strengthened walls are significantly influenced by the CFRP strip configurations [69].

The mechanical characteristics and environmental effect of fibre-reinforced rubberized concrete (RFRRC) are evaluated and explored in the work of Xiong and colleagues [70]. The RFRRC exhibits ductility, good flexural toughness, and impact resistance based on the experimental results. As a result, the RFRRC holds promise for application in civil infrastructure, including impact barriers, playground flooring, concrete pavements, and earthquake-resistant buildings [70]. The porosity of the combination rises with the addition of RCFRP fibres, and the strengths of the mixtures including fibres rose marginally in comparison to the mixtures without fibres (Fig. 5). For instance, R0CF15's 1.5% fibre dosage by volume results in a compressive strength of 59.42 MPa, which is 5.5% greater than the specimen made of plain concrete (56.31 MPa). This is because RCFRP fibres can offer concrete lateral confinement and limit the spread of cracks in the material, making up for the strength loss brought on by porosity. Moreover, Fig. 8 shows that, in comparison to combinations without RCR, the compressive strengths of the mixtures containing RCR dramatically dropped by about 40% [70].

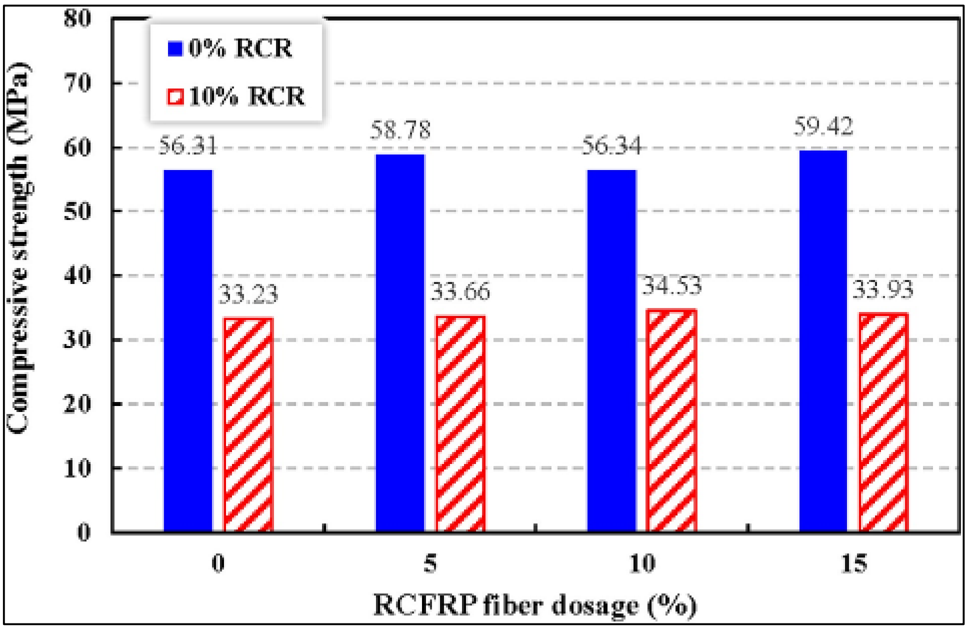

Figure 5 Compressive strength [70]

Similarly, Figure 6 displays the failure photos of every combo. Brittle shear failure was experienced by R0CF0, as seen in Fig. 6a [70]. There was a significant degree of concrete spalling noted, and the failing specimen had weak integrity. The specimens containing RCFRP fibers have entirely different failure mechanisms. After achieving the peak load, a significant number of vertical and diagonal cracks may be seen because of the RCFRP fibres. The specimens retained good integrity because of the bridging action that the RCFRP fibres provided (Fig. 6b–d), demonstrating that the ductility of the RCFRP fibre reinforced concrete is superior to that of ordinary concrete. Comparable breakdown modes are shown by the rubberized concrete specimens (Figs. 6e–h) and their counterparts in Figs. 6a–d [70].

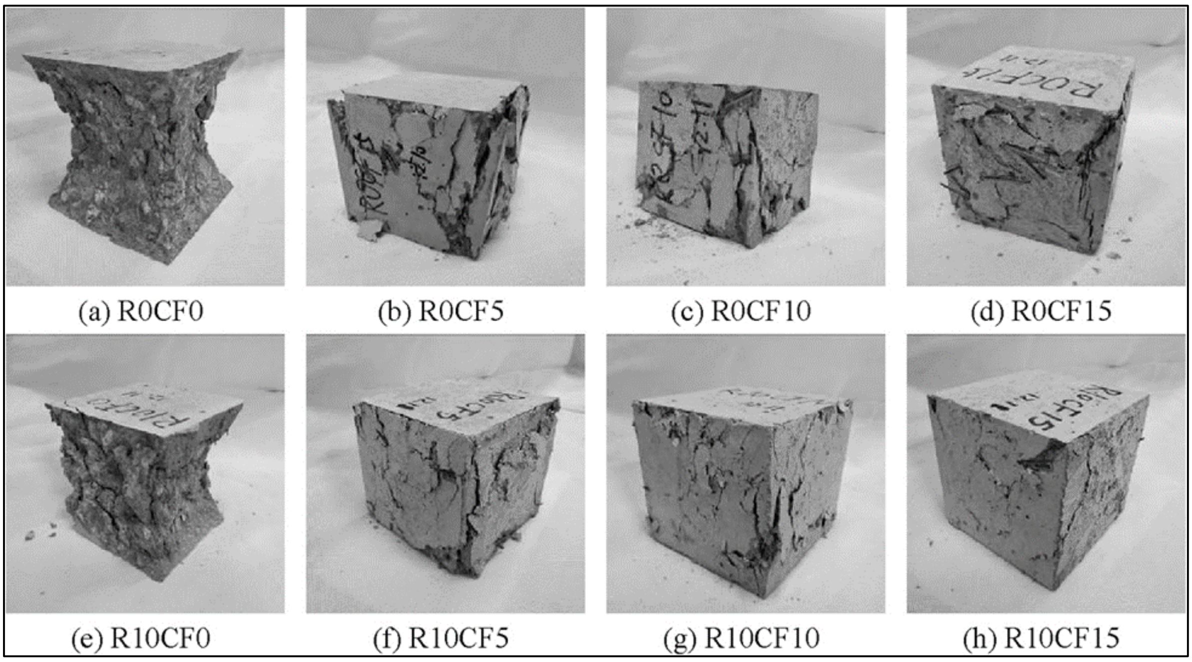

Figure 6 Failure modes [70]

6.2. Reinforcement of Concrete beam

Beams made of reinforced concrete (RC) frequently fail flexurally and shearly. Most RC beams need to have their load-carrying capacity strengthened in order to withstand early failure and increase durability [71]. There are numerous ways to strengthen RC beams, but one popular technique is to utilize externally bonded sheets or plates made of high-strength materials including polyester, steel plates, fibre-reinforced polymer, wire mesh, and textile fabrics. CFRP is one of these polymers that is frequently used to strengthen RC beams. Some of the special qualities of CFRP are its non-corrosiveness, stiffness, strength-to-weight ratio, resistance to fungi, insects, and chemicals, low heat transmissibility, and ease of installation [72].

Research on the efficient application of fibre-reinforced polymer (FRP) adhered to concrete surfaces is still ongoing on a global scale. The use of externally bonded FRP in the strengthening and restoration of reinforced concrete structures has advanced significantly during the past three decades. Experimental experiments were conducted by Sidikka et al. on RC beams that were externally strengthened with CFRP strips in flexure. The beams' flexural behaviour and failure modes were examined. The discussion of CFRP strain efficiency in connection to various strengthening mechanisms was also covered[73]. Shannag et al. conducted experimental tests on concrete beams strengthened for flexure strengthening. They also examined the permissible tensile strain of FRP-strengthened RC beams in relation to design code requirements [74].

6.3. Concrete slabs

By connecting concrete slabs to the underside and minimizing deflection, CFRP can improve their flexural strength and structural integrity [75]. Türer et al. (2023) examined the strain behaviour, energy dissipation capacity, maximum bearing capacity, and starting stiffness as characteristics while analysing the effectiveness of CFRP strips in strengthening flat slabs [76]. They used ABAQUS to generate a model, and in order to do so, they made nineteen slab samples. These samples were then placed next to the column and reinforced with CFRP strips that were fastened with fan-style anchors [76]. Following the investigation, the presence of anchored CFRP strips increased the load-carrying capability by 50%. The use of CFRP sheets and a self-locking mechanism to reinforce [77]the RC slab at the end anchoring to stop the deboning was discovered by Zhou et al . Six one-way CFRP slabs were subjected to a four-point bending test (Fig. 7). By using the hybrid anchored (HA) CFRP technique of strengthening, the bonding was effectively improved by 46% and the ultimate load was raised. The employment of the CFRP rate will decrease to 28% with the longer bond, and further investigation is necessary when strengthening with CFRP sheets.

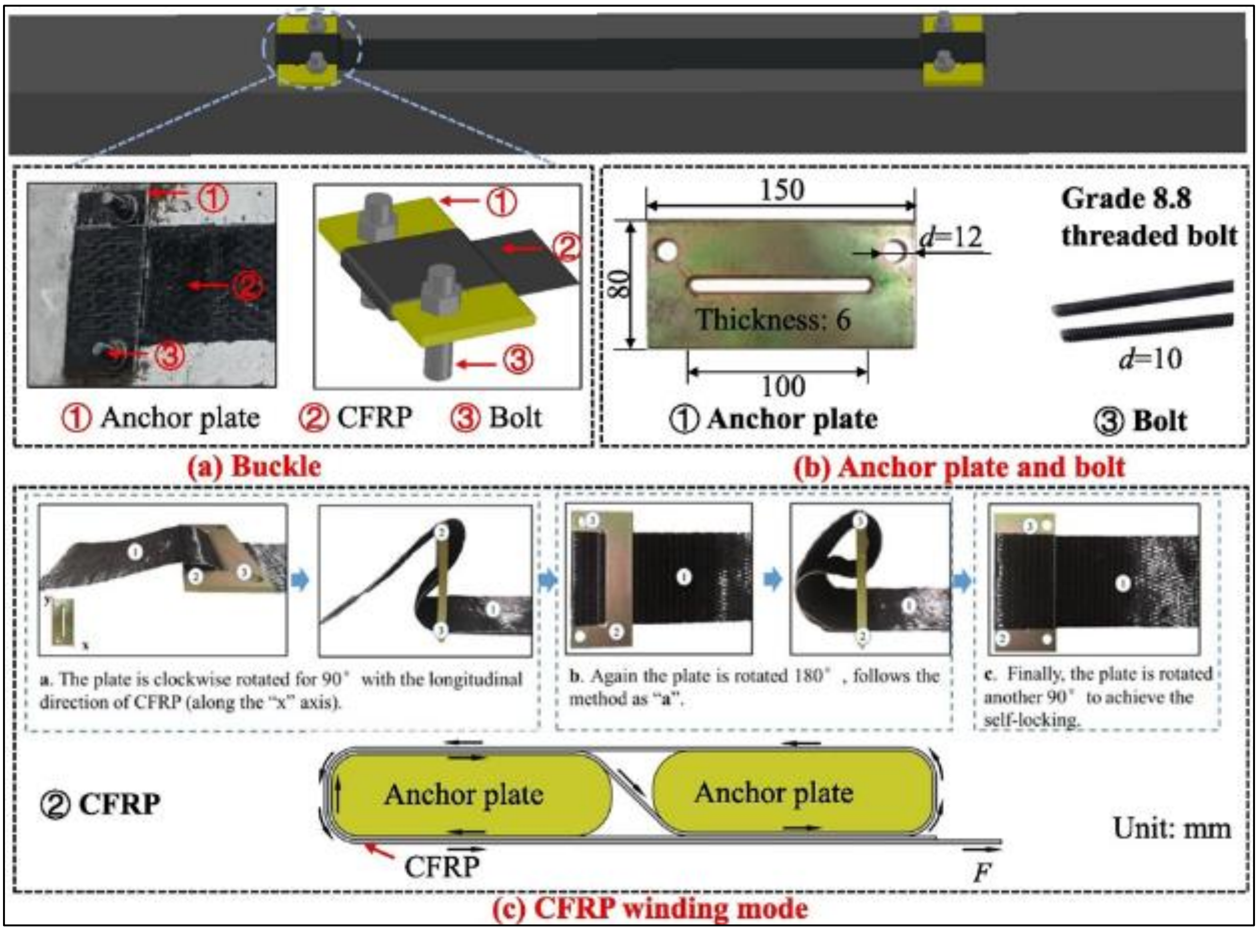

Figure 7 Self-locking of carbon-fiber reinforced polymers (CFRP) through winding around slotted plates [77]

Chen et al [78]investigated reinforced concrete slab-column connections reinforced with carbon fibre reinforced polymer (CFRP) laminates. The results demonstrated that the punching shear strength of concrete slab-column connections was greatly increased using externally bonded CFRP laminates. There was a discernible improvement in slabs with a decreased steel-reinforcing ratio. The CSR2 series of specimens (1.2% steel reinforcement ratio) and the CSR1 series of specimens (0.6% steel reinforcement ratio) showed higher percentages of CFRP-strengthened specimens' ultimate strength when compared to the specimens without laminates. The increases ranged from 16.9 to 40.9% and 51.4 to 67.5%, respectively[78]. Among the specimens, two unique behavioural types were identified. Consequently, the specimens fall into two categories of failure: flexural failure and punched shear failure. Two specimens, CSR1-C1-F0 and CSR1-C2-F0 (without laminates), on the tension side of the slab exhibited flexural cracking that extended to the corners and along the slab's diagonal direction. These two specimens ultimately failed in flexure, as shown in Figure 8a, and on the tension side of the slab, they showed a typical yield line failure mechanism. The usual patterns of cracking that appeared when the slabs failed to punch are seen in Figures 7b,c. There was no cracking inside the truncated cone because the laminates reinforced the CFRP-strengthened specimens (Fig. 8c). On the other hand, more cracking was visible inside the truncated cone in specimens CSR2-C1-F0 and CSR2-C2-F0 (which lacked laminates) (Fig. 8b) [78].

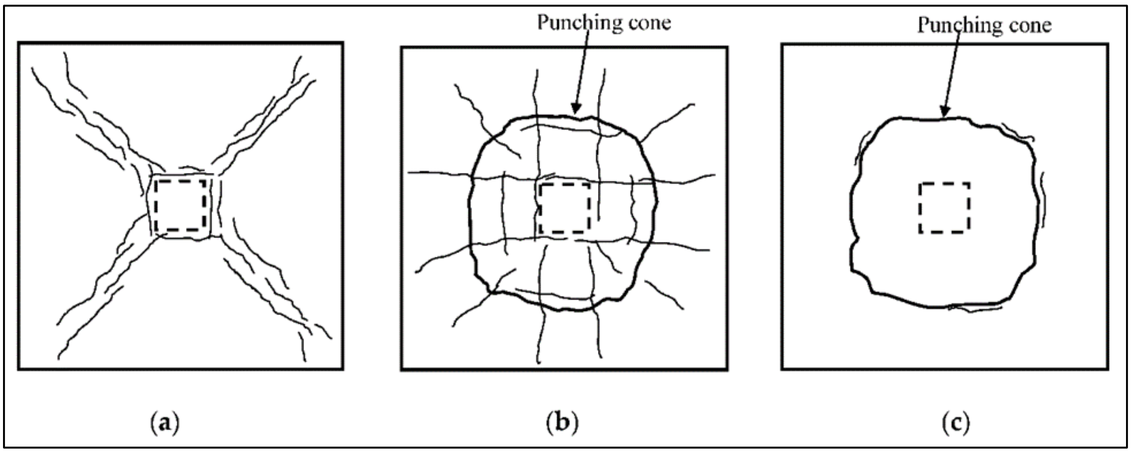

Figure 8 Cracking look on the tension surface of the slab: (a) Flexural failure; (b) Punching shear failure of slabs without CFRP laminates; (c) Punching shear failure of slabs with CFRP laminates [78]

6.4. Reinforced Concrete columns

A column made of reinforced concrete (RC) is regarded as one of the most crucial structural components [79]. If the RC column fails, the structure may collapse partially or completely. An RC column may reach a point where it is unable to properly withstand the load being applied to it. Construction errors, structural deformation, blasts, neglect, earthquakes, deformation resulting from seismic load, and brief exposure to heat are some of the factors that can lead to the degradation of RC concrete columns' load-displacement behaviour [80]. Enhancing their capability and prolonging their service life may be best achieved by strengthening and repairing the structural parts. Strengthening and repairing the structural element is typically more cost-effective than replacing it because doing so would require a significant financial outlay.

CFRP is now regarded as one of the best materials for reinforcing and repairing structural elements, particularly RC concrete columns, because of its remarkable performance [81]. Furthermore, it takes a lot of time and labour to strengthen and restore concrete columns using conventional methods such steel jacketing. Fiber Reinforced Polymer (FRP) composites, such as external FRP wrapping and FRP spraying, can be used to repair and strengthen reinforced concrete columns. There are several reasons why columns would need to be strengthened in order to improve their axial, shear, and flexural capacities: corrosion, accidental hits, eccentric loading, and seismic loading [82].

To regulate the local buckling of the steel tube and offer the quasiplastic range of work of the CFT, Du et al. [83]investigated CFRP as an additional material for CFT columns. Excellent seismic performance is provided by the added CFRP reinforcement, as demonstrated by the acquired axial compression test results [84–87]. Numerous studies have been conducted on circular CFT columns reinforced with CFRP [88] . The kind, stiffness, and number of layers of CFRP confinement, as well as the thickness of the steel tube, were shown by researchers to have a major effect on the ductility and load-carrying capability of CFT columns. Square CFT columns reinforced with CFRP were evaluated by Prabhu et al . The findings of this experiment demonstrated that the application of CFRP raised the confining pressure on the CFT columns. Columns reinforced with CFRP have a bigger deformation and a higher ultimate load in comparison to CFT columns [83].

Radhi et al [89] reported corroded columns can be effectively restored to strength and ductility via CFRP-wrapping. The load and strain capacities of both CFRP-confined and unconfined columns were examined in this work. The specimens for columns underwent an AC procedure, were enveloped in CFRP, and underwent tests to assess their failure modes, material deterioration, and compressive response. It is possible to conclude the following: When compared to a single layer of CFRP, wrapping the corroded columns with two layers enhanced their ultimate axial strain and strength capability. This results from the corroded columns' increased rigidity and subsequent confinement pressure [89].

6.5. The potential of CFRP waste for recycling

In the circular economy, recycling is essential, especially when the materials have structural characteristics that allow for effective conversion [90] . The circular economy generally decreases waste through enhanced materials, technologies, processes, and core business innovation, as well as by using renewable energy and doing away with hazardous substances [91]. Key players in the worldwide carbon fibre recycling market segments include Carbon Conversions Ltd., ELG Carbon Fiber Ltd., Karborek Ltd., Mitsubishi Ltd., and several others. When the capacity reaches

100 tons/year, ELG Carbon Fiber Ltd., for instance, recycles carbon fibres that retain at least 90% of their tensile strength at a cost 40% less than vCF, with a carbon fibre reuse price of just $15/kg. After thorough analysis, the majority of recoverable materials—mainly fibres and resin breakdown products—show that they are regenerable [92].

Due to its low weight and superior mechanical properties, CFRC have long since displaced more conventional materials in high-performance applications [93]. While polyacrylonitrile (PAN) and pitch precursors currently account for most carbon fibres produced globally, the chemistry of basic carbonization greatly benefits from the pyrolysis of cellulosic fibers and the subsequent production of high-modulus carbon fibres [90]. More than 90% of the carbon fibres that are widely sold worldwide are now produced using PAN, a non-renewable material derived from petroleum. Carbon fibers based on PAN are mainly produced using two methods. The initial step involves generating a PAN precursor, which mostly entails polymerizing monomers and producing a spinning liquid that is spun further. This initial step in the synthesis of carbon fibre is crucial since the specification of the precursor determines the carbon fibre's efficiency. In the next step, the precursor is pre-oxidized and carbonized [94].

Carbon fibre is a material that exhibits great adaptability and holds great potential across various industries [95]. Carbon fibre is a great material option for lightweight and durable applications, such as those in the automotive, sporting goods, and aerospace industries, because of its remarkable strength-to-weight ratio. In aircraft, carbon fibre is widely used for structural components due to its high temperature tolerance and significant weight reduction. The aviation sector is highly focused on cutting fuel consumption and carbon dioxide (CO_2) emissions. Since the 1960s, airline firms have reduced CO_2 emissions by 70%, and they plan to continue doing so until 2050 thanks to technological and operational breakthroughs [96].

The use of carbon fibre has been expanding significantly this year and is still growing daily due to the growing demand for lightweight materials [96]. To create a circular economy, the scientific and industrial domains are working together to create frameworks for the recovery, refurbishing, and recycling of end-of-life objects. The vast potential of carbon fibre after its life cycle can be attributed to its various applications. Using premium PAN carbon fibres, the aerospace industry accounts for 36% of the global market, with the automobile sector contributing 24%.

Table 2 provides some instances of how recycled carbon fibre reinforced polymers are used and reused.

Table 2 Recycled carbon fiber reinforced polymers use and reuse

Feedstock	**Recycling process**	**New Material Matrix**	**Process condition**	**Mechanical properties**	**Ref**
CFR epoxy	Crushing	ABS/PP	CFRTP (CFRP + thermoplastic polymer) is pelletized using a two-axis pelletizing machine and then injected.	Composite: The mechanical qualities appear to be limited by a fiber volume fraction of 24%.	[97]
CFR epoxy	Mechanical cutting	Epoxy	Fibers are processed through a wet papermaking process to create non-woven mats. Seven MPa compression molding	rCF is 95.6% TM 2 and 98.1% TS 1 in comparison to virgin fibers.	[98]
CFR epoxy and CFR bismaleimide	cutting using a machine, pyrolysis at 400 °C, cleaning with water washing, and fiber drying	PPS	Pelletizing with a twin-screw extruder requires air cooling, a die temperature of 315 °C, a screw speed of 150 rpm, and a throughput of three kg/h. Production at 290–305 degrees Celsius using a molding press	Comparing Composite to PPS, there is a 680% TM, 720% TS, and 250% impact energy gain.	[99]

CFR epoxy	pulverized with a moving blade in a ball mill	ABS	Injection, Grinding, and Mixing	Composite: Greater TS at increasing CF content, but a sharp decline at 70% (weight)	[100]
CFR polybenzoxazine	Crushing by hand and then pyrolyzing at 500 degrees Celsius	LDPE	Roll mill speed and temperature for blending: 10–20 rpm, 150–180 °C. Hot-pressed and grounded at 180°C and 34.5 MPa.	rCF: Some rCF + additive combinations exhibit qualities that are comparable to those of vCF composites.	[101]
CFR PEEK	Electrodynamical fragmentation, 6 cycles of 100 pulses, 180 kV, frequency 5 Hz, followed by sieving	PEEK	Compression molding using a 20-ton clamping force, three minutes of 360°C heat, and 20°C cooling rate	Composite: Compared to novel composite, rCFRP mechanical performance is 17% worse.	[102]
PAN-rCF	-	PC	Pelletizing with a twin-screw extruder: die temperature between 230 and 250 °C, screw speed of 100 rpm. Injection (rCF + biocarbon fillers) at 250 °C and 80–120 MPa	Composite: increased by 35% TM 270% TS above the reference PC-biocarbon composite	[103]
CFR epoxy	Pyrolysis in 360°C molten $ZnCl_2$	Epoxy	Hand lay-up, oven-cured for 2 hours at 80 °C and 4 hours at 150 °C.	When it comes to TS retention after pyrolysis in molten ZnCl2 and 80% TS retention after pyrolysis in air, rCF performs better than vCF.	[104]

7. Challenges and outlooks

Although carbon fiber reinforced polymers (CFRP) provide many potential benefits, there are a number of obstacles preventing its widespread use. Despite recent reductions, the high cost of the composite structure continues to be a major obstacle in the manufacturing of CFRP, affecting its cost-effectiveness [105]. This is caused by two factors: first, the price of the material itself; and second, the technique used in the design of composite elements. However, because of its light weight, the structure may be assembled more easily and with smaller, less expensive foundations, which helps to lower the overall cost of the construction. Additionally, compared to steel or concrete structures, composite constructions have a high degree of endurance, which over time means lower repair and maintenance costs [106].

The use of CFRP in structural applications to enhance characteristics poses a significant challenge to recycling of composites as their useful lives are coming to an end. Therefore, swift and decisive action to lower greenhouse gas emissions is needed to address the current environmental crisis, which has reached a critical point [107]. The goal of developing recycling techniques for CFRP composites is to reduce expenses in half while enhancing the composite's lifespan economy. Because carbon fibres are non-polar, interfacial adhesion is difficult to achieve, requiring pre-manufacturing surface treatments that add time and expense but are essential to improving compatibility between fibres and polymers. Furthermore, unlike carbon fibres, polymers have limits when it comes to withstanding oxidation and high temperatures, which complicates the production process. Unlike metals, CFRP is still hard to predict for fatigue qualities, making it difficult to estimate fatigue failure accurately [108]. Additionally, CFRP composites are stiff and abrasive, making machining them challenging and necessitating specific tools and machining techniques. Moreover, another significant challenge when using CFRP in engineering works is the fluctuations in the behaviour of CFRP under different temperature conditions, which in turn affect their practical applications. significant engineering challenge is how CFRP behaves when temperatures fluctuate. This may pose some fire risks and during regular use [109].

Even though a lot of research is being done to expand the applications of CFRP in structural building applications, more in-depth analysis and applied research are still needed to close the knowledge gap between CFRP research and commercialization. Yet, a few issues remain that prevent CFRP from being widely used, including the difficulties of anchoring, the fire safety issue, and the relatively high cost. Hence, continuous research using latest technological tools as described in this review will go a long way in advancing the utility of CFRP as high-performance structural material [109].

8. Conclusions

The use of carbon fibre-reinforced polymers for use in building demonstrates how versatile and highly potential they are to further civil engineering. The remarkable mechanical characteristics that result from the combination of the strength of carbon fibres and the polymer matrix make CFRPs ideal for demanding construction applications. In the building sector, CFRP has become a highly effective composite material with several benefits. It is very desirable for many different structural applications due to its outstanding features, which include a high modulus of elasticity, higher strength-to-weight ratio, fatigue strength, and tensile strength compared to other FRP composites. By using CFRP as external reinforcement and lamination, concrete slabs, beams, and columns can have much greater ductility and flexural strength. This approach lessens the need for traditional reinforcement while also preventing corrosion or degradation-related early failure. Furthermore, the remarkable resilience of CFRP to fire and chemicals makes it more appropriate for use in challenging conditions. The benefits of CFRP in construction outweigh drawbacks like its comparatively high cost and requirement for specialised installation methods, making it a material that is appealing for the future of the industry. By using it, structures may become more resilient to environmental influences like climate change and remain safer, more resilient, and more sustainable. It is anticipated that construction companies will prioritize the development and implementation of CFRP for structural applications as manufacturing processes continue to evolve and CFRP becomes more widely available. This tendency will make it possible to create sustainable and resilient constructions that can survive upcoming difficulties. CFRP can completely transform and strengthen the construction industry with further research and development.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

All authors have no conflict of interests to declare

References

[1] J.R. Cromwell, K.A. Harries, B.M. Shahrooz, Environmental durability of externally bonded FRP materials intended for repair of concrete structures, Constr Build Mater 25 (2011) 2528–2539. https://doi.org/10.1016/J.conbuildmat.2010.11.096.

[2] D. Mostofinejad, A. Akhlaghi, Experimental Investigation of the Efficacy of EBROG Method in Seismic Rehabilitation of Deficient Reinforced Concrete Beam–Column Joints Using CFRP Sheets, Journal of Composites for Construction 21 (2017). https://doi.org/10.1061/(asce)cc.1943-5614.0000781.

[3] J. Xie, Z. Lu, Y. Guo, Y. Huang, Durability of CFRP sheets and epoxy resin exposed to natural hygrothermal or cyclic wet-dry environment, Polym Compos 40 (2019) 553–567. https://doi.org/10.1002/PC.24687.

[4] B.G. Charalambidi, T.C. Rousakis, A.I. Karabinis, Analysis of the fatigue behavior of reinforced concrete beams strengthened in flexure with fiber reinforced polymer laminates, Compos B Eng 96 (2016) 69–78. https://doi.org/10.1016/J.compositesb.2016.04.014.

[5] A. Siddika, K. Saha, M.S. Mahmud, S.C. Roy, M.A. Al Mamun, R. Alyousef, Performance and failure analysis of carbon fiber-reinforced polymer (CFRP) strengthened reinforced concrete (RC) beams, SN Appl Sci 1 (2019). https://doi.org/10.1007/S42452-019-1675-X.

[6] A. Siddika, M.A. Al Mamun, R. Alyousef, Y.H.M. Amran, Strengthening of reinforced concrete beams by using fiber-reinforced polymer composites: A review, Journal of Building Engineering 25 (2019). https://doi.org/10.1016/J.jobe.2019.100798.

[7] M.M.A. Alhadid, A.M. Soliman, M.L. Nehdi, M.A. Youssef, Critical overview of blast resistance of different concrete types, Magazine of Concrete Research 66 (2014) 72–81. https://doi.org/10.1680/macr.13.00096.

[8] L.C. Meneghetti, M.R. Garcez, L.C.P. Da Silva Filho, F.P.S.L. De Gastal, Fatigue life regression model of reinforced concrete beams strengthened with FRP, Magazine of Concrete Research 63 (2011) 539–549. https://doi.org/10.1680/macr.2011.63.7.539.

[9] A.H. Al-Saidy, A.S. Al-Harthy, K.S. Al-Jabri, M. Abdul-Halim, N.M. Al-Shidi, Structural performance of corroded RC beams repaired with CFRP sheets, Compos Struct 92 (2010) 1931–1938. https://doi.org/10.1016/J.compstruct.2010.01.001.

[10] S.S. Zhang, T. Yu, G.M. Chen, Reinforced concrete beams strengthened in flexure with near-surface mounted (NSM) CFRP strips: Current status and research needs, Compos B Eng 131 (2017) 30–42. https://doi.org/10.1016/J.compositesb.2017.07.072.

[11] M. Zarringol, M. Zarringol, A Comparative Study on the Efficiency of CFRP and GFRP in the Improvement of Compressive Strength, Acoustic Impedance and Bracing of Filled and Hollow Concrete Columns in Different Layers and Ages, J Sustain Dev 9 (2016) 110. https://doi.org/10.5539/jsd.v9n5p110.

[12] J. Zhang, M.A. Delichatsios, T. Fateh, M. Suzanne, S. Ukleja, Characterization of flammability and fire resistance of carbon fibre reinforced thermoset and thermoplastic composite materials, J Loss Prev Process Ind 50 (2017) 275–282. https://doi.org/10.1016/J.JLP.2017.10.004.

[13] M.Y. Shen, Z.H. Guo, W.T. Feng, A study on the characteristics and thermal properties of modified regenerated carbon fiber reinforced thermoplastic composite recycled from waste wind turbine blade spar, Compos B Eng 264 (2023). https://doi.org/10.1016/j.compositesb.2023.110878.

[14] K.B.M. Ismail, M.A. Kumar, S. Mahalingam, B. Raj, J. Kim, Carbon fiber-reinforced polymers for energy storage applications, J Energy Storage 84 (2024). https://doi.org/10.1016/j.est.2024.110931.

[15] M. xin Xu, X. xi Meng, H. wen Ji, J. Yang, J. yi Di, Y. chang Wu, Q. Lu, Evolution of pyrolysis char during the recovery of carbon fiber reinforced polymer composite and its effects on the recovered carbon fiber, J Environ Chem Eng 12 (2024). https://doi.org/10.1016/j.jece.2024.112214.

[16] F. Micelli, R. Mazzotta, M. Leone, M.A. Aiello, Review Study on the Durability of FRP-Confined Concrete, Journal of Composites for Construction 19 (2015). https://doi.org/10.1061/(asce)CC.1943-5614.0000520.

[17] T. El Maaddawy, K. Soudki, Carbon-Fiber-Reinforced Polymer Repair to Extend Service Life of Corroded Reinforced Concrete Beams, Journal of Composites for Construction 9 (2005) 187–194. https://doi.org/10.1061/(ASCE)1090-0268(2005)9:2(187).

[18] R. Hsissou, R. Seghiri, Z. Benzekri, M. Hilali, M. Rafik, A. Elharfi, Polymer composite materials: A comprehensive review, Compos Struct 262 (2021) 113640. https://doi.org/10.1016/J.compstruct.2021.113640.

[19] A. Gillet, O. Mantaux, G. Cazaurang, Characterization of composite materials made from discontinuous carbon fibres within the framework of composite recycling, Compos Part A Appl Sci Manuf 75 (2015) 89–95. https://doi.org/10.1016/j.compositesa.2015.05.002.

[20] K. Obunai, T. Fukuta, K. Ozaki, Carbon fiber extraction from waste CFRP by microwave irradiation, Compos Part A Appl Sci Manuf 78 (2015) 160–165. https://doi.org/10.1016/j.compositesa.2015.08.012.

[21] B.A. Newcomb, Processing, structure, and properties of carbon fibers, Compos Part A Appl Sci Manuf 91 (2016) 262–282. https://doi.org/10.1016/j.compositesa.2016.10.018.

[22] T. Ramakrishnan, M.D. Mohan Gift, S. Chitradevi, R. Jegan, P. Subha Hency Jose, H.N. Nagaraja, R. Sharma, P. Selvakumar, S.M. Hailegiorgis, Study of Numerous Resins Used in Polymer Matrix Composite Materials, Advances in Materials Science and Engineering 2022 (2022). https://doi.org/10.1155/2022/1088926.

[23] Y. Xu, Y. Liu, S. Chen, Y. Ni, Current Overview of Carbon Fiber: Toward Green Sustainable Raw Materials, Bioresources 15 (2020) 7234–7259. https://doi.org/10.15376/biores.15.3.XU.

[24] D. Shen, Q. Yang, Y. Jiao, Z. Cui, J. Zhang, Experimental investigations on reinforced concrete shear walls strengthened with basalt fiber-reinforced polymers under cyclic load, Constr Build Mater 136 (2017) 217–229. https://doi.org/10.1016/J.conbuildmat.2016.12.102.

[25] F. Elgabbas, E.A. Ahmed, B. Benmokrane, Physical and mechanical characteristics of new basalt-FRP bars for reinforcing concrete structures, Constr Build Mater 95 (2015) 623–635. https://doi.org/10.1016/J.conbuildmat.2015.07.036.

[26] P. Cousin, M. Hassan, P. V. Vijay, M. Robert, B. Benmokrane, Chemical resistance of carbon, basalt, and glass fibers used in FRP reinforcing bars, J Compos Mater 53 (2019) 3651–3670. https://doi.org/10.1177/0021998319844306/ASSET/IMAGES/LARGE/10.1177_0021998319844306-FIG15.jpeg.

[27] Q. Zhang, J. Liu, R. Sager, L. Dai, J. Baur, Hierarchical composites of carbon nanotubes on carbon fiber: Influence of growth condition on fiber tensile properties, Compos Sci Technol 69 (2009) 594–601. https://doi.org/10.1016/J.compscitech.2008.12.002.

[28] A.Q. Bhatti, N. Kishi, K.H. Tan, Impact resistant behaviour of RC slab strengthened with FRP sheet, Materials and Structures/Materiaux et Constructions 44 (2011) 1855–1864. https://doi.org/10.1617/S11527-011-9742-9.

[29] N. van de Werken, H. Tekinalp, P. Khanbolouki, S. Ozcan, A. Williams, M. Tehrani, Additively manufactured carbon fiber-reinforced composites: State of the art and perspective, Addit Manuf 31 (2020). https://doi.org/10.1016/j.addma.2019.100962.

[30] B. Karaş, P.J. Smith, J.P.A. Fairclough, K. Mumtaz, Additive manufacturing of high density carbon fibre reinforced polymer composites, Addit Manuf 58 (2022) 103044. https://doi.org/10.1016/J.addma.2022.103044.

[31] L.G. Blok, M.L. Longana, H. Yu, B.K.S. Woods, An investigation into 3D printing of fibre reinforced thermoplastic composites, Addit Manuf 22 (2018) 176–186. https://doi.org/10.1016/j.addma.2018.04.039.

[32] Y. Nam, S. Lee, S.M. Jee, J. Bang, J.H. Kim, J.H. Park, High efficiency upcycling of post-consumer acrylonitrile-butadiene-styrene via plasma-assisted mechanochemistry, Chemical Engineering Journal 480 (2024) 147960. https://doi.org/10.1016/J.cej.2023.147960.

[33] J. You, H.H. Choi, Y.M. Lee, J. Cho, M. Park, S.S. Lee, J.H. Park, Plasma-assisted mechanochemistry to produce polyamide/boron nitride nanocomposites with high thermal conductivities and mechanical properties, Compos B Eng 164 (2019) 710–719. https://doi.org/10.1016/J.compositesb.2019.01.100.

[34] Y.M. Lee, J. You, M. Kim, T.A. Kim, S.S. Lee, J. Bang, J.H. Park, Highly improved interfacial affinity in carbon fiber-reinforced polymer composites via oxygen and nitrogen plasma-assisted mechanochemistry, Compos B Eng 165 (2019) 725–732. https://doi.org/10.1016/J.compositesb.2019.02.021.

[35] S. Dariushi, A.M. Rezadoust, R. Kashizadeh, Effect of processing parameters on the fabrication of fiber metal laminates by vacuum infusion process, Polym Compos 40 (2019) 4167–4174. https://doi.org/10.1002/PC.25277.

[36] S. van Oosterom, T. Allen, M. Battley, S. Bickerton, An objective comparison of common vacuum assisted resin infusion processes, Compos Part A Appl Sci Manuf 125 (2019). https://doi.org/10.1016/j.compositesa.2019.105528.

[37] T. Wang, K. Huang, L. Guo, T. Zheng, F. Zeng, An automated vacuum infusion process for manufacturing high-quality fiber-reinforced composites, Compos Struct 309 (2023) 116717. https://doi.org/10.1016/J.compstruct.2023.116717.

[38] S. Yuan, J. Bai, C.K. Chua, J. Wei, K. Zhou, Material evaluation and process optimization of CNT-coated polymer powders for selective laser sintering, Polymers (Basel) 8 (2016). https://doi.org/10.3390/polym8100370.

[39] N.A. Charoo, S.F. Barakh Ali, E.M. Mohamed, M.A. Kuttolamadom, T. Ozkan, M.A. Khan, Z. Rahman, Selective laser sintering 3D printing–an overview of the technology and pharmaceutical applications, Drug Dev Ind Pharm 46 (2020) 869–877. https://doi.org/10.1080/03639045.2020.1764027.

[40] H. Tang, H. Chen, Q. Sun, Z. Chen, W. Yan, Experimental and computational analysis of structure-property relationship in carbon fiber reinforced polymer composites fabricated by selective laser sintering, Compos B Eng 204 (2021) 108499. https://doi.org/10.1016/J.compositesb.2020.108499.

[41] J. Guo, J. Bai, K. Liu, J. Wei, Surface quality improvement of selective laser sintered polyamide 12 by precision grinding and magnetic field-assisted finishing, Mater Des 138 (2018) 39–45. https://doi.org/10.1016/j.matdes.2017.10.048.

[42] A. Jansson, L. Pejryd, Characterisation of carbon fibre-reinforced polyamide manufactured by selective laser sintering, Addit Manuf 9 (2016) 7–13. https://doi.org/10.1016/j.addma.2015.12.003.

[43] N. Raphael, K. Namratha, B.N. Chandrashekar, K.K. Sadasivuni, D. Ponnamma, A.S. Smitha, S. Krishnaveni, C. Cheng, K. Byrappa, Surface modification and grafting of carbon fibers: A route to better interface, Progress in Crystal Growth and Characterization of Materials 64 (2018) 75–101. https://doi.org/10.1016/J.pcrysgrow.2018.07.001.

[44] L. Liu, C. Jia, J. He, F. Zhao, D. Fan, L. Xing, M. Wang, F. Wang, Z. Jiang, Y. Huang, Interfacial characterization, control and modification of carbon fiber reinforced polymer composites, Compos Sci Technol 121 (2015) 56–72. https://doi.org/10.1016/J.compscitech.2015.08.002.

[45] C.C. Knight, C. Zeng, C. Zhang, B. Wang, Recycling of woven carbon-fibre-reinforced polymer composites using supercritical water, Environ Technol 33 (2012) 639–644. https://doi.org/10.1080/09593330.2011.586732.

[46] C.C. Knight, C. Zeng, C. Zhang, R. Liang, Fabrication and properties of composites utilizing reclaimed woven carbon fiber by sub-critical and supercritical water recycling, Mater Chem Phys 149–150 (2015) 317–323. https://doi.org/10.1016/J.matchemphys.2014.10.023.

[47] A.K. Kulkarni, S. Daneshvarhosseini, H. Yoshida, Effective recovery of pure aluminum from waste composite laminates by sub- and super-critical water, J Supercrit Fluids 55 (2011) 992–997. https://doi.org/10.1016/J.supflu.2010.09.007.

[48] R. Piñero-Hernanz, J. García-Serna, C. Dodds, J. Hyde, M. Poliakoff, M.J. Cocero, S. Kingman, S. Pickering, E. Lester, Chemical recycling of carbon fibre composites using alcohols under subcritical and supercritical conditions, J Supercrit Fluids 46 (2008) 83–92. https://doi.org/10.1016/J.supflu.2008.02.008.

[49] Y. Fu, H. Li, W. Cao, Enhancing the interfacial properties of high-modulus carbon fiber reinforced polymer matrix composites via electrochemical surface oxidation and grafting, Compos Part A Appl Sci Manuf 130 (2020) 105719. https://doi.org/10.1016/J.compositesa.2019.105719.

[50] H. Jiang, Y. Wang, C. Wang, X. Xu, M. Li, Z. Xu, H. Tan, Y. Wang, Effect of electrochemical anodization and growth time on continuous growth of carbon nanotubes on carbon fiber surface, Ceram Int 48 (2022) 29695–29704. https://doi.org/10.1016/J.ceramint.2022.06.227.

[51] V. Fiore, F. Di Franco, R. Miranda, M. Santamaria, D. Badagliacco, A. Valenza, Effects of anodizing surface treatment on the mechanical strength of aluminum alloy 5083 to fibre reinforced composites adhesive joints, Int J Adhes Adhes 108 (2021) 102868. https://doi.org/10.1016/J.ijadhadh.2021.102868.

[52] F. Cheng, Y. Hu, X. Zhang, X. Hu, Z. Huang, Adhesive bond strength enhancing between carbon fiber reinforced polymer and aluminum substrates with different surface morphologies created by three sulfuric acid solutions, Compos Part A Appl Sci Manuf 146 (2021) 106427. https://doi.org/10.1016/J.compositesa.2021.106427.

[53] J. You, S.M. Jee, Y.M. Lee, S.S. Lee, M. Park, T.A. Kim, J.H. Park, Carbon fiber-reinforced polyamide composites with efficient stress transfer via plasma-assisted mechanochemistry, Composites Part C: Open Access 6 (2021) 100209. https://doi.org/10.1016/J.jcomc.2021.100209.

[54] K.Y. Rhee, S.J. Park, D. Hui, Y. Qiu, Effect of oxygen plasma-treated carbon fibers on the tribological behavior of oil-absorbed carbon/epoxy woven composites, Compos B Eng 43 (2012) 2395–2399. https://doi.org/10.1016/J.compositesb.2011.11.046.

[55] D.J. Eyckens, K. Jarvis, A.J. Barlow, Y. Yin, L.C. Soulsby, Y. Athulya Wickramasingha, F. Stojcevski, G. Andersson, P.S. Francis, L.C. Henderson, Improving the effects of plasma polymerization on carbon fiber using a surface modification pretreatment, Compos Part A Appl Sci Manuf 143 (2021) 106319. https://doi.org/10.1016/J.compositesa.2021.106319.

[56] A. Duongthipthewa, Y. Su, L. Zhou, Electrical conductivity and mechanical property improvement by low-temperature carbon nanotube growth on carbon fiber fabric with nanofiller incorporation, Compos B Eng 182 (2020) 107581. https://doi.org/10.1016/J.compositesb.2019.107581.

[57] C. Wang, Y. Wang, S. Su, Optimization of Process Conditions for Continuous Growth of CNTs on the Surface of Carbon Fibers, Journal of Composites Science 2021, Vol. 5, Page 111 5 (2021) 111. https://doi.org/10.3390/jcs5040111.

[58] J. Qin, C. Wang, R. Lu, S. Su, Z. Yao, L. Zheng, Q. Gao, Y. Wang, Q. Wang, H. Wei, Uniform growth of carbon nanotubes on carbon fiber cloth after surface oxidation treatment to enhance interfacial strength of composites, Compos Sci Technol 195 (2020) 108198. https://doi.org/10.1016/J.compscitech.2020.108198.

[59] A.Y. Boroujeni, M. Al-Haik, Carbon nanotube – Carbon fiber reinforced polymer composites with extended fatigue life, Compos B Eng 164 (2019) 537–545. https://doi.org/10.1016/J.compositesb.2018.11.056.

[60] W.K.M. Frhaan, B.H. Abu Bakar, N. Hilal, A.I. Al-Hadithi, CFRP for strengthening and repairing reinforced concrete: a review, Innovative Infrastructure Solutions 6 (2021) 1–13. https://doi.org/10.1007/S41062-020-00417-5/tables/2.

[61] D.S. Vijayan, A. Sivasuriyan, P. Devarajan, A. Stefańska, Ł. Wodzyński, E. Koda, Carbon Fibre-Reinforced Polymer (CFRP) Composites in Civil Engineering Application—A Comprehensive Review, Buildings 2023, Vol. 13, Page 1509 13 (2023) 1509. https://doi.org/10.3390/buildings13061509.

[62] J. Liu, P. Tran, V. Nguyen Van, C. Gunasekara, S. Setunge, 3D printing of cementitious mortar with milled recycled carbon fibres: Influences of filament offset on mechanical properties, Cem Concr Compos 142 (2023) 105169. https://doi.org/10.1016/J.cemconcomp.2023.105169.

[63] B. Täljsten, L. Elfgren, Strengthening concrete beams for shear using CFRP-materials: evaluation of different application methods, Compos B Eng 31 (2000) 87–96. https://doi.org/10.1016/S1359-8368(99)00077-3.

[64] C.A. Issa, A. AbouJouadeh, Carbon Fiber Reinforced Polymer Strengthening of Reinforced Concrete Beams: Experimental Study, Journal of Architectural Engineering 10 (2004) 121–125. https://doi.org/10.1061/(asce)1076-0431(2004)10:4(121)/

[65] Q. Fang, J. Zhang, Three-dimensional modelling of steel fiber reinforced concrete material under intense dynamic loading, Constr Build Mater 44 (2013) 118–132. https://doi.org/10.1016/J.conbuildmat.2013.02.067.

[66] T.C. Triantafillou, E. Choutopoulou, E. Fotaki, M. Skorda, M. Stathopoulou, K. Karlos, FRP confinement of wall-like reinforced concrete columns, Materials and Structures/Materiaux et Constructions 49 (2016) 651–664. https://doi.org/10.1617/S11527-015-0526-5.

[67] W. Ferdous, A.D. Almutairi, Y. Huang, Y. Bai, Short-term flexural behaviour of concrete filled pultruded GFRP cellular and tubular sections with pin-eye connections for modular retaining wall construction, Compos Struct 206 (2018) 1–10. https://doi.org/10.1016/J.compstruct.2018.08.025.

[68] Z. Huang, J. Shen, H. Lin, X. Song, Y. Yao, Shear behavior of concrete shear walls with CFRP grids under lateral cyclic loading, Eng Struct 211 (2020) 110422. https://doi.org/10.1016/J.engstruct.2020.110422.

[69] A.S. Mosallam, A. Nasr, Structural performance of RC shear walls with post-construction openings strengthened with FRP composite laminates, Compos B Eng 115 (2017) 488–504. https://doi.org/10.1016/j.compositesb.2016.06.063.

[70] C. Xiong, Q. Li, T. Lan, H. Li, W. Long, F. Xing, Sustainable use of recycled carbon fiber reinforced polymer and crumb rubber in concrete: mechanical properties and ecological evaluation, J Clean Prod 279 (2021) 123624. https://doi.org/10.1016/j.jclepro.2020.123624.

[71] C. Del Vecchio, M. Di Ludovico, A. Balsamo, A. Prota, G. Manfredi, M. Dolce, Experimental Investigation of Exterior RC Beam-Column Joints Retrofitted with FRP Systems, Journal of Composites for Construction 18 (2014). https://doi.org/10.1061/(asce)cc.1943-5614.0000459.

[72] C. Del Vecchio, M. Di Ludovico, A. Prota, G. Manfredi, Modelling beam-column joints and FRP strengthening in the seismic performance assessment of RC existing frames, Compos Struct 142 (2016) 107–116. https://doi.org/10.1016/J.compstruct.2016.01.077.

[73] A. Siddika, M.H.H. Shojib, M.M. Hossain, M.I. Hossain, M.A. Al Mamun, R. Alyousef, Y.H.M. Amran, Flexural performance of wire mesh and geotextile-strengthened reinforced concrete beam, SN Appl Sci 1 (2019). https://doi.org/10.1007/S42452-019-1373-8.

[74] M.J. Shannag, N.M. Al-Akhras, S.F. Mahdawi, Flexure strengthening of lightweight reinforced concrete beams using carbon fibre-reinforced polymers, Structure and Infrastructure Engineering 10 (2014) 604–613. https://doi.org/10.1080/15732479.2012.757790.

[75] F.A. Fathelbab, M.S. Ramadan, A. Al-Tantawy, Strengthening of RC bridge slabs using CFRP sheets, Alexandria Engineering Journal 53 (2014) 843–854. https://doi.org/10.1016/j.aej.2014.09.010.

[76] A. Türer, Ö. Mercimek, Ö. Anıl, Y. Erbaş, Experimental and numerical investigation of punching behavior of two-way RC slab with different opening locations and sizes strengthened with CFRP strip, Structures 49 (2023) 918–942. https://doi.org/10.1016/j.istruc.2023.01.157.

[77] C. Zhou, L. Wang, Y. Wang, Z. Fang, Experimental study on the flexural strengthening of one-way RC slabs with end-buckled and/or externally bonded CFRP sheets, Eng Struct 282 (2023) 115832. https://doi.org/10.1016/j.engstruct.2023.115832.

[78] C.C. Chen, S.L. Chen, Strengthening of Reinforced Concrete Slab-Column Connections with Carbon Fiber Reinforced Polymer Laminates, Applied Sciences 2020, Vol. 10, Page 265 10 (2019) 265. https://doi.org/10.3390/app10010265.

[79] D.-S. Gu, G. Wu, Z.-S. Wu, Y.-F. Wu, Confinement Effectiveness of FRP in Retrofitting Circular Concrete Columns under Simulated Seismic Load, Journal of Composites for Construction 14 (2010) 531–540. https://doi.org/10.1061/(asce)cc.1943-5614.0000105.

[80] E. del Rey Castillo, M. Griffith, J. Ingham, Seismic behavior of RC columns flexurally strengthened with FRP sheets and FRP anchors, Compos Struct 203 (2018) 382–395. https://doi.org/10.1016/J.compstruct.2018.07.029.

[81] R.D. Iacobucci, S.A. Sheikh, O. Bayrak, Retrofit of Square Concrete Columns with Carbon Fiber-Reinforced Polymer for Seismic Resistance, ACI Struct J 100 (2003) 785–794. https://doi.org/10.14359/12845.

[82] L.J. Ouyang, W.Y. Gao, B. Zhen, Z.D. Lu, Seismic retrofit of square reinforced concrete columns using basalt and carbon fiber-reinforced polymer sheets: A comparative study, Compos Struct 162 (2017) 294–307. https://doi.org/10.1016/j.compstruct.2016.12.016.

[83] Y. Du, Y. Zhang, Z. Chen, S. Dong, X. fang Deng, K. Qian, Seismic behavior of CFRP confined rectangular CFST columns using high-strength materials: Numerical analysis and restoring force model, Structures 34 (2021) 4237–4253. https://doi.org/10.1016/j.istruc.2021.10.010.

[84] Y. Yan, S. Li, Y. Lu, A. Zheng, CFST columns strengthened with CFRP textile grid-reinforced engineered cementitious composites under eccentric compression, Compos Struct 289 (2022) 115498. https://doi.org/10.1016/J.COMPSTRUCT.2022.115498.

[85] Q. Shen, K. Li, J. Wang, F. Wang, Z. Hu, G. Li, Cyclic behaviour of circular CFT-SG columns under axial tension-compression: Novel FE modelling and design methods, Structures 62 (2024) 106148. https://doi.org/10.1016/J.istruc.2024.106148.

[86] K. Ostrowski, M. Dudek, Ł. Sadowski, Compressive behaviour of concrete-filled carbon fiber-reinforced polymer steel composite tube columns made of high performance concrete, Compos Struct 234 (2020) 111668. https://doi.org/10.1016/j.compstruct.2019.111668.

[87] J. Li, Q. Shen, J. Wang, F. Wang, G. Li, Axially-compressed behavior of carbon-FRP strengthening CFT short columns having circumferential void defects, J Constr Steel Res 213 (2024) 108316. https://doi.org/10.1016/j.jcsr.2023.108316.

[88] G. Ganesh Prabhu, M.C. Sundarraja, Y.Y. Kim, Compressive behavior of circular CFST columns externally reinforced using CFRp composites, Thin-Walled Structures 87 (2015) 139–148. https://doi.org/10.1016/j.tws.2014.11.005.

[89] M.S. Radhi, M.S. Hassan, I.N. Gorgis, Carbon fibre-reinforced polymer confinement of corroded circular concrete columns, Journal of Building Engineering 43 (2021) 102611. https://doi.org/10.1016/j.jobe.2021.102611.

[90] J. Zhang, V.S. Chevali, H. Wang, C.H. Wang, Current status of carbon fibre and carbon fibre composites recycling, Compos B Eng 193 (2020) 108053. https://doi.org/10.1016/j.compositesb.2020.108053.

[91] K.O. Otun, S.O. Amusat, I.T. Bello, J. Abdulsalam, A.T. Ajiboye, A.A. Adeleke, S.O. Azeez, Recent advances in the synthesis of various analogues of MOF-based nanomaterials: A mini-review, Inorganica Chim Acta 536 (2022) 120890. https://doi.org/10.1016/j.ica.2022.120890.

[92] H. Huang, W. Liu, Z. Liu, An additive manufacturing-based approach for carbon fiber reinforced polymer recycling, CIRP Annals 69 (2020) 33–36. https://doi.org/10.1016/j.cirp.2020.04.085.

[93] C.H. Chen, C.L. Chiang, J.X. Wang, M.Y. Shen, A circular economy study on the characterization and thermal properties of thermoplastic composite created using regenerated carbon fiber recycled from waste thermoset CFRP bicycle part as reinforcement, Compos Sci Technol 230 (2022) 109761. https://doi.org/10.1016/J.compscitech.2022.109761.

[94] J.A. Liu, Z.Q. Dong, X.Y. Zhu, al -, E. Tang, X. Wang, L. Li, I.N. Dammulla, G.M. Swain, H. Sukanto, W. Wisnu Raharjo, D. Ariawan, J. Triyono, Carbon fibers recovery from CFRP recycling process and their usage: A review, IOP Conf Ser Mater Sci Eng 1034 (2021) 012087. https://doi.org/10.1088/1757-899x/1034/1/012087.

[95] H.T. Ali, R. Akrami, S. Fotouhi, M. Bodaghi, M. Saeedifar, M. Yusuf, M. Fotouhi, Fiber reinforced polymer composites in bridge industry, Structures 30 (2021) 774–785. https://doi.org/10.1016/j.istruc.2020.12.092.

[96] A. Akbar, K.M. Liew, Assessing recycling potential of carbon fiber reinforced plastic waste in production of eco-efficient cement-based materials, J Clean Prod 274 (2020) 123001. https://doi.org/10.1016/J.JCLEPRO.2020.123001.

[97] K.H. Wong, D. Syed Mohammed, S.J. Pickering, R. Brooks, Effect of coupling agents on reinforcing potential of recycled carbon fibre for polypropylene composite, Compos Sci Technol 72 (2012) 835–844. https://doi.org/10.1016/j.compscitech.2012.02.013.

[98] S. Pimenta, S.T. Pinho, P. Robinson, K.H. Wong, S.J. Pickering, Mechanical analysis and toughening mechanisms of a multiphase recycled CFRP, Compos Sci Technol 70 (2010) 1713–1725. https://doi.org/10.1016/j.compscitech.2010.06.017.

[99] K. Stoeffler, S. Andjelic, N. Legros, J. Roberge, S.B. Schougaard, Polyphenylene sulfide (PPS) composites reinforced with recycled carbon fiber, Compos Sci Technol 84 (2013) 65–71. https://doi.org/10.1016/j.compscitech.2013.05.005.

[100] M. Okayasu, T. Yamazaki, K. Ota, K. Ogi, T. Shiraishi, Mechanical properties and failure characteristics of a recycled CFRP under tensile and cyclic loading, Int J Fatigue 55 (2013) 257–267. https://doi.org/10.1016/J.IJFATIGUE.2013.07.005.

[101] J.A. Onwudili, N. Miskolczi, T. Nagy, G. Lipóczi, Recovery of glass fibre and carbon fibres from reinforced thermosets by batch pyrolysis and investigation of fibre re-using as reinforcement in LDPE matrix, Compos B Eng 91 (2016) 154–161. https://doi.org/10.1016/J.compositesb.2016.01.055.

[102] M. Roux, N. Eguémann, C. Dransfeld, F. Thiébaud, D. Perreux, Thermoplastic carbon fibre-reinforced polymer recycling with electrodynamical fragmentation: From cradle to cradle, Journal of Thermoplastic Composite Materials 30 (2017) 381–403. https://doi.org/10.1177/0892705715599431/ASSET/IMAGES/LARGE/10.1177_0892705715599431-fig19.jpeg.

[103] J. Andrzejewski, M. Misra, A.K. Mohanty, Polycarbonate biocomposites reinforced with a hybrid filler system of recycled carbon fiber and biocarbon: Preparation and thermomechanical characterization, J Appl Polym Sci 135 (2018) 46449. https://doi.org/10.1002/app.46449.

[104] T. Wu, W. Zhang, X. Jin, X. Liang, G. Sui, X. Yang, Efficient reclamation of carbon fibers from epoxy composite waste through catalytic pyrolysis in molten ZnCl2, RSC Adv 9 (2018) 377–388. https://doi.org/10.1039/c8ra08958b.

[105] M. Hashimoto, T. Okabe, T. Sasayama, H. Matsutani, M. Nishikawa, Prediction of tensile strength of discontinuous carbon fiber/polypropylene composite with fiber orientation distribution, Compos Part A Appl Sci Manuf 43 (2012) 1791–1799. https://doi.org/10.1016/j.compositesa.2012.05.006.

[106] P. Jagadeesh, M. Puttegowda, P. Boonyasopon, S.M. Rangappa, A. Khan, S. Siengchin, Recent developments and challenges in natural fiber composites: A review, Polym Compos 43 (2022) 2545–2561. https://doi.org/10.1002/pc.26619.

[107] J. Zhang, G. Lin, U. Vaidya, H. Wang, Past, present and future prospective of global carbon fibre composite developments and applications, Compos B Eng 250 (2023) 110463. https://doi.org/10.1016/J.Compositesb.2022.110463.

[108] M.S.H. Al-Furjan, L. Shan, X. Shen, M.S. Zarei, M.H. Hajmohammad, R. Kolahchi, A review on fabrication techniques and tensile properties of glass, carbon, and Kevlar fiber reinforced rolymer composites, Journal of Materials Research and Technology 19 (2022) 2930–2959. https://doi.org/10.1016/J.Jmrt.2022.06.008.

[109] F.G. Alabtah, E. Mahdi, F.F. Eliyan, The use of fiber reinforced polymeric composites in pipelines: A review, Compos Struct 276 (2021) 114595. https://doi.org/10.1016/J.Compstruct.2021.114595.