Chapter

Fibre-Reinforced Polymer (FRP) in Civil Engineering

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Abstract

Construction produces a third of global carbon emissions. These emissions cause global warming and contribute to climate emergency. There is a need to encourage use of sustainable and eco-friendly materials to effectively deal with climate emergency. Fibre-reinforced polymer (FRP) is an eco-friendly material with low-carbon footprint. FRP composites in civil engineering are mainly used in three applications: (1) FRP profiles in new-build; (2) FRP-reinforcing bar in concrete members and (3) FRP in repair and rehabilitation of existing structures. This chapter presents basic properties of constituent materials (fibres and polymer resins), mechanical properties of FRP bars, strengthening systems and profiles, manufacturing processes and civil engineering applications of FRP composites. Durability, sustainability and recycling of FRP composites are also discussed.

Keywords: FRP structures, FRP in buildings and bridges, FRP in structural engineering, resins and fibres, sustainability of FRP, durability of FRP, recycling of FRP

1. Introduction

Buildings and construction sector produces 39% of global carbon emissions [1–5]. Construction uses a wide variety of materials, ranging from cement to clay, wood to steel and aluminium to glass. Traditional construction materials, such as reinforced concrete, steel, masonry and timber, have a long track record of proven strength and reliability. The construction guidelines and design standards are also well established for these materials. However, these conventional materials have limitations as well. Steel can corrode; concrete and masonry are weak in tension; and timber can shrink and rot. The conventional materials are usually energy-intensive to produce. To reduce carbon emissions and protect and restore the natural environment, there is need to develop and invest in new sustainable construction technologies and materials. Fibre-reinforced polymer (FRP) composite is such an eco-friendly material with lower ecological impact than the usual construction materials [6–9]. Use of FRPs in new-build and repair of existing structures has been increasing over past few decades [10]. There are three main FRP shapes in civil engineering: (1) all-FRP profiles for new-build; (2) FRP-reinforcing bars in concrete members; and (3) FRP sheets for repair of existing structures.

Fibre-reinforced polymer (FRP) composites have been used in various civil engineering applications, buildings and bridges included, for over five decades. Their use in aerospace, marine and automotive industries even goes back to 1930s. FRPs also have their applications in sports and rail sector and wind turbines [7, 8]. For structural use, FRP composites are usually made by embedding fibres in a polymer matrix. The matrix consists of polyester, vinylester, or epoxy resins and fibres include glass, carbon, or aramid fibres. The resin binds the fibres together, while fibres provide strength and stiffness to the finished FRP product. The main aim is to produce a lightweight strong and stiff component [11].

FRP composites have desirable properties for use in structural engineering. Lightweight, chemical and corrosion resistance, low ecological footprint, fast deployment, electromagnetic transparency and thermal insulation of glass FRPs, and high strength-to-weight ratio, offsite fabrication and modular construction, superior durability and mouldability are some of the main benefits of FRP for structural use [12]. FRP composites are versatile and customisable. The ability to mould into complex shapes creates new aesthetic possibilities and provides geometrically efficient design solutions [12, 13]. Some FRPs using aramid have high impact resistance and are often used in bulletproof vests, helmets, and automotive crash attenuators [7, 8, 14]. But structural use of FRP with aramid fibres is limited. FRP composite material is not an ideal material though. Like classical structural materials, FRPs have shortcomings too. The notable weakness is the brittle nature of the FRP material. It is linear elastic up to failure. FRPs fail in a sudden brittle manner without giving warning. However, in a real world, FRP components are never loaded to failure. They are normally loaded up to a third of their failure load. Anisotropy and low transverse properties of FRPs are few other drawbacks. Lack of ductility and limited knowledge about fire and durability performances and no agreed design codes for FRP structures are some of the main setbacks hindering wider acceptance of this material.

FRP composites are suitable in structural applications where challenging environmental conditions exist and fast installation is needed. Due to their chemical, corrosion and environmental resistances, FRPs perform better in harsh environments compared with the traditional materials. Besides use in repair market, and as rebars in concrete members, full FRP profiles are used in chemical and food processing plants, wastewater treatment plants, cooling towers, foot and road bridges, bridges decks and edge elements, and railway platforms as primary structural elements. FRP elements are also used in secondary structures, such as insulated ladders, floor gratings, stairways with handrails, working platforms and walkways, and building façade panels [1, 7].

This chapter is organised into six sections. First section gives the context and background to use of FRP material in civil engineering applications. Constituent materials and manufacturing processes of FRP products are presented in Section 2. Input materials, such as fibres and polymer resins, are discussed in the section. FRP manufacturing methods including automatic and manual processes are also explained in Section 2. Section 3 is focused on applications of FRP material in civil engineering. Three main applications include FRP profiles, rebars and strengthening systems. Section 4 relates to durability aspects of FRP composites. Various environmental factors, structural health monitoring and field evaluation of FRP materials and structures are described in the section. Section 5 is about sustainability of FRP composites. Lifespan of FRP composites, including extraction and production of FRP material, manufacturing, use and end-of-life disposal are discussed in this section. Section 5 also expands on recycling methods of FRP, such as incineration, thermal, chemical and mechanical recycling. Finally, Section 6 highlights the key conclusions of the work presented in the chapter.

2. Constituent materials and manufacturing processes

Composite materials are formed by combining two or more materials to represent the best properties of the constituent materials. The resulting composite material accounts for weaknesses of the individual materials and leads to strong and stiff structural components. Constituent materials and manufacturing processes of FRP-reinforcing bars, structural profiles and strengthening sheets are described in this section.

2.1 Materials

FRP composites consist of the fibres embedded in a polymer matrix. Fibres provide strength and stiffness. The matrix serves as a glue that ensures transfer of forces among the fibres, the applied loads and the composite component [7].

2.1.1 Fibres

Typical fibres used in strengthening and new-build applications are glass, carbon and aramid. These are man-made synthetic fibres [1]. More recently, the research focus has moved to sustainable composites with natural fibres, such as basalt fibres [15]. Typical mechanical properties of various fibres are listed in **Table 1**. The strength and modulus in this table are for plain fibres; the values for manufactured FRP composites, such as pultruded profiles, bars and sheets, will be considerably lower than the plain fibres. All fibres have linear elastic stress–strain response with no yielding [16].

Glass fibres are the most commonly used fibres in structural composites. They are used in structural profiles, reinforcing bars and strengthening applications. Glass fibres are available in four different grades: E-glass (electrical glass), A-glass (window glass), C-glass (corrosion resistant, also known as AR-glass or alkali-resistant glass) and S-glass (structural or high-strength glass). E-glass is the most popular one due to its relatively low cost and electrical insulation properties. S-glass has higher tensile strength and modulus than E-glass. S-glass is normally used in aerospace industry due to its high strength [1, 7, 8, 14, 17]. S-glass is almost four times more expensive than E-glass [1]. Except AR-glass, all other glass types are prone to alkaline attack. Glass fibres are non-conductive to electricity and can be easily used near electrified railway lines, communication facilities and power lines [18]. Glass fibres are commercially available as unidirectional rovings, as shown in **Figure 1(a)**.

Carbon fibres are the strongest of all fibres. They are used for strengthening applications, such as CFRP strips, sheets, rebars and prestressing tendons. Carbon fibres possess high tensile strength and modulus, high fatigue and creep resistances, and superior chemical resistance [7]. Due to these properties, carbon fibres are highly resistant to aggressive environments. The key disadvantages of carbon fibres are their high cost, thermal conductivity and anisotropy. Carbon fibres are 10–30 times more expensive than E-glass fibres [1, 16, 18]. As carbon fibres are conductive to electricity, they should be electrically isolated from any steel parts. Usually, the resin provides the electrical insulation, but glass fibres should be used instead in conductive

Material		Grade	Density (g/cm^3)	Tensile modulus (GPa)	Tensile strength (MPa)	Max elongation (%)	Fibre architecture	Glass transition temperature (°C)
Fibre	Glass	E	2.57	72.5	3400	2.5	Isotropic	—
		A	2.46	73.0	2760	2.5		
		C	2.46	74.0	2350	2.5		
		S	2.47	88.0	4600	3.0		
	Carbon	Standard	1.70	250.0	3700	1.2	Anisotropic	—
		High strength	1.80	250.0	4800	1.4		
		High modulus	1.90	500.0	3000	0.5		
		Ultrahigh modulus	2.10	800.0	2400	0.2		
	Aramid	—	1.40	70.0–190.0	2800–4100	2.0–2.4	Anisotropic	—
	Basalt	—	2.6–2.8	90–110	4100–4800	3.2	Anisotropic	—
Polymer resin	Polyester	—	1.20	4.0	65	2.5	—	70–120
	Epoxy	—	1.20	3.0	90	8	—	100–270
	Vinylester	—	1.12	3.5	82	6	—	102–150
	Phenolic	—	1.24	2.5	40	1.8	—	260
	Polyurethane	—	varies	2.9	71	5.9	—	135–140 [21]

Table 1.
Properties of plain fibres and thermosetting polymer resins [1, 7, 8, 16].

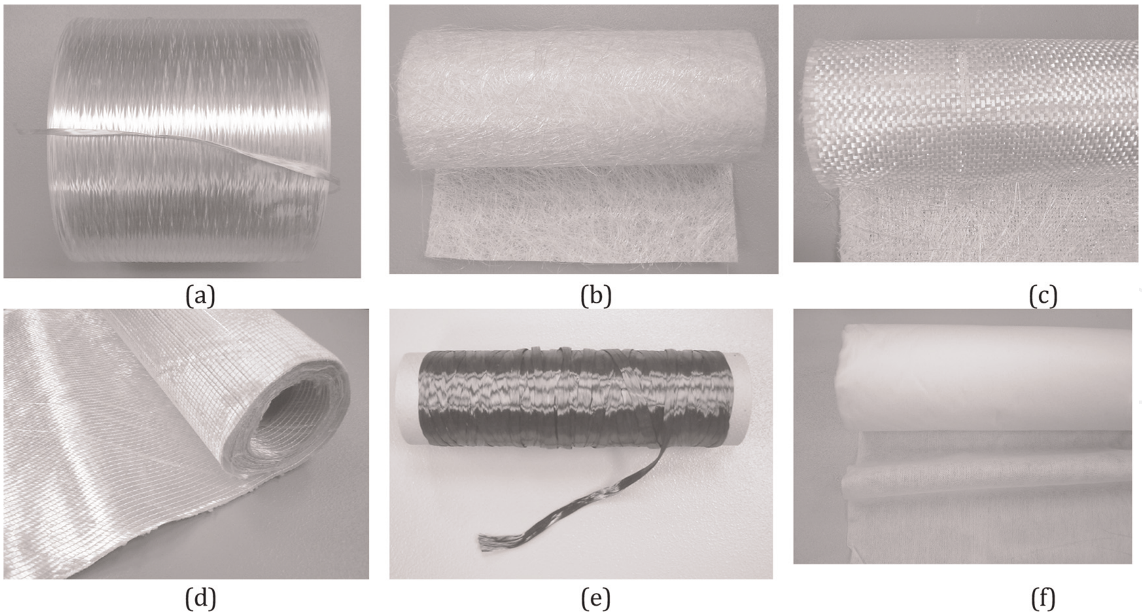

(a) (b) (c) (d) (e) (f)

Figure 1.
Different fibre system for pultrusion (adapted from Bank [8]): (a) glass roving on a spool; (b) E-glass continuous filament mat (CFM) or continuous strand mat (CSM); (c) woven glass fabric; (d) stitched glass fabric; (e) carbon fibre tows; (f) polyester veil.

environments [16]. Carbon fibres come in long and continuous tows, containing bundles of 1000 to 16,000 parallel filaments [18], as shown in **Figure 1(e)**. Carbon fibres have four different strength grades: standard modulus (SM), intermediate modulus (IM), high strength (HS) and ultrahigh modulus (UHM). Glass and carbon fibres are not sensitive to the ultraviolet (UV) light [16].

Though not very common in structural engineering applications, aramid or Kevlar fibres are still used in FRP rebars and prestressing tendons. Aramid fibres have their compressive strength 20% less than the tensile strength. Their behaviour is linear elastic and brittle under tension, and non-linear and ductile under compression. They exhibit large plasticity in compression when subjected to bending. This behaviour increases the impact resistance of aramid fibres [18, 19]. Due to high energy absorption and toughness resistance, aramid fibres are used in bullet-proof vests and helmets [14]. Aramid fibres are affected by UV light; they change colour under UV and the strength is reduced. Aramid fibres are resistant to most chemical attacks, except few acids and alkalis. They can crack at high moisture content [16, 18]. Relatively low compressive strength (500–1000 MPa), sensitivity to UV light and tendency to stress rupture make aramid fibres less suitable for structural applications [7]. However, AFRP bars are sometime preferred over CFRP-reinforcing bars in high alkaline environments due to their relatively lower cost [20].

Basalt fibres are single-component materials produced by melting crushed volcanic lava deposits. Basalt is a natural material found in these volcanic rocks. Basalt rock is abundant; about 33% of Earth's crust is basalt. The manufacturing process of basalt fibres is similar to glass fibres, but with no additives. This makes basalt fibres less expensive than glass or carbon fibres. Basalt fibres have similar mechanical properties as glass fibres. The benefits of basalt fibres include heat and fire resistance, excellent thermal and acoustic insulation, cheaper cost than carbon and glass fibres, resistance to UV, chemicals and moisture, excellent dielectric insulation and excellent temperature resistance from −260°C to 700°C. Research in structural use of basalt fibres is still at very early stages. Experimental studies are available on other natural fibres, such as hemp, sisal, flax and bamboo fibres. But commercial FRP products using these fibres are not available yet [7, 15, 18, 20, 22]. With more focus on climate emergency and global warming, the key drivers for future FRP composites will be sustainability, recycling and reuse, and eco-friendliness of materials. Possible replacement of synthetic fibres with natural fibres is reviewed in a recent paper [23]. Fibres are used in various forms [14]:

- Rovings—parallel bundles of continuous untwisted filaments (**Figure 1(a)**)
- Yarn—bundles of twisted filaments
- Fibre mats with chopped or continuous fibres (**Figure 1(b)**)
- Woven and non-woven fabrics (**Figure 1(c)**)
- Stitched fabrics, grid, mesh and fleece (**Figure 1(d)**)
- Carbon fibre tows (**Figure 1(e)**)

2.1.2 Resins

Matrix, or simply polymer or resin are different names for polymer resins. Resins bind the fibres together. It is a non-fibrous part of the FRP composite [8]. The resin serves many functions: it protects fibres from environmental degradation (moisture) and mechanical abrasion, keeps the fibres in position within the composite component, transfers load between fibres and prevents fibres from buckling in compression. The matrix constitutes 30–60% by volume of a FRP composite system [7, 18]. Resins are of two types—thermosetting and thermoplastic resins. These resins are different based on how the polymer chains are connected. Material properties of thermosetting resins are given in **Table 1**. The glass transition temperature (T_g, °C) of a polymer resin is the temperature at which an amorphous polymer moves from a hard or glassy state to a softer, often rubbery, or viscous or sticky state. The glass transition temperature of the unidirectional FRP composite component is usually taken equal to the glass transition temperature of the resin matrix [8].

In thermosetting resins or polymers, molecular chains are cross-linked and have strong bonds. This means once the thermosetting polymer is set after curing, it cannot be remoulded to a different shape. Excellent binding properties and low viscosity (flowy nature) of thermoset resins allow easy placement of fibres within the FRP composite system. Thermoset resins include polyester, epoxy, vinylester, phenolic and polyurethane. Conversely, thermoplastic resins are mouldable due to weak molecular bonds. Their molecular chains are not cross-linked too. They can be reshaped, repeatedly softened and hardened by temperature cycles above their forming temperature. They remain plastic and do not set. They can also be recycled and reprocessed. Due to high viscosity (gluey nature) and poor adhesion properties, it is hard to impregnate fibres in thermoplastic resins. This increases the manufacturing cost of FRP composites. There are four types of thermoplastic matrices: polypropylene, polyamide, polyethylene and polybutylene. Their strength and stiffness are lower than the thermosetting resins. Thermoplastic resins are used in aerospace engineering. Their use in structural engineering applications is rare. Most FRP products in civil engineering applications use thermoelastic resins

[1, 7, 8, 18]. Most resins are susceptible to UV light. Special additives and surface fleece/veil are needed for their protection. Resins are isotropic non-linear visco-elastic materials [7, 14].

FRP profiles and bars mainly use polyester and vinylester resins. Almost 75% of FRP products use polyester resins [7]. Polyester resin is less expensive compared to vinylester. Identical FRP structural profiles using both polyester and vinylester resins are produced [8] by many manufacturers [24–26]. FRP reinforcement bars utilise vinylester resin due to its corrosion resistance and durability performance. Phenolic resins have excellent fire resistance and are the oldest resins. They cost the same as polyester resins. However, their use in structural FRP products is scarce due to difficulty in reinforcing and curing them. They are only used in walkway gratings and strengthening strips for timber structural components [8]. Polyurethane resin matrix characterises high toughness. When used with glass fibres, it can produce high tensile and impact resistant FRP part. The cost of polyurethane is similar to the vinylester resin [1].

2.1.3 Additives and fillers

FRP structural products contain more ingredients than simply fibres and resins. Fillers are added to the polymer resin to reduce the cost of FRP products and improve some properties. Filler content varies from 10% to 30% of the resin weight. Fillers increase the hardness, creep, fatigue and chemical resistances of FRP composites. They also reduce the shrinkage cracks and improve the fire behaviour of FRP parts. Additives are also added to the resin system to improve certain properties. Additive content is usually less than 1% of the resin weight. Resins contain various additives, such as catalysts, accelerators, hardeners, curing agents, pigments, ultraviolet stabilisers, fire retardants and mould release agents. Additives and fillers alter the physical and mechanical properties of FRP components [7, 8].

2.2 Manufacturing processes

FRP products, such as rebars, strips and profiles, are produced using two methods: automatic process (pultrusion) and manual process (hand or wet layup). FRP rebars, strips and profiles use pultrusion. While, hand layup is used for FRP sheets for onsite strengthening of existing structures [7, 8]. There are other specialised methods, such as filament winding, centrifugation, resin transfer moulding (RTM), resin infusion moulding (RIM) and vacuum-assisted resin transfer moulding (VARTM). FRP tubular sections and piles are made through filament winding method. FRP decks and components are produced by RTM, RIM and VARTM methods. More recently, 3D-printed continuous FRP composites have also been produced; further details can be found in [27, 28].

2.2.1 Pultrusion

Pultrusion is an automatic process of producing constant cross-sectional FRP profiles, rebars and strips. Open sections, like wide-flanged sections, closed tubular sections and multicellular profiles can be produced using pultrusion. The part has to be straight; curved section cannot be pultruded [8, 29, 30]. Schematic diagram of pultrusion process including different stages of pultrusion is shown in **Figure 2**. Pultrusion machines have fibre and matrix units. The fibre unit contains fibre

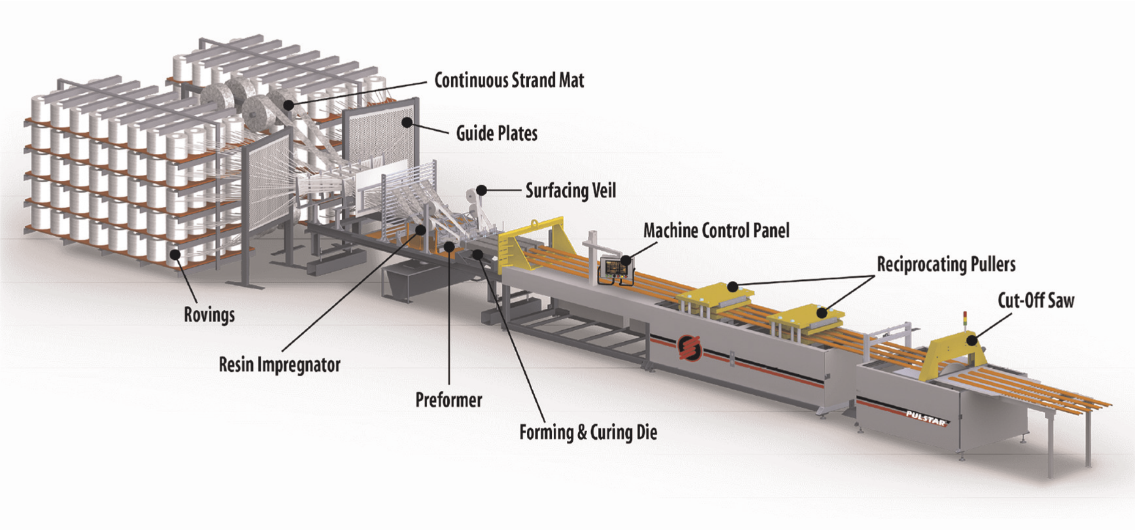
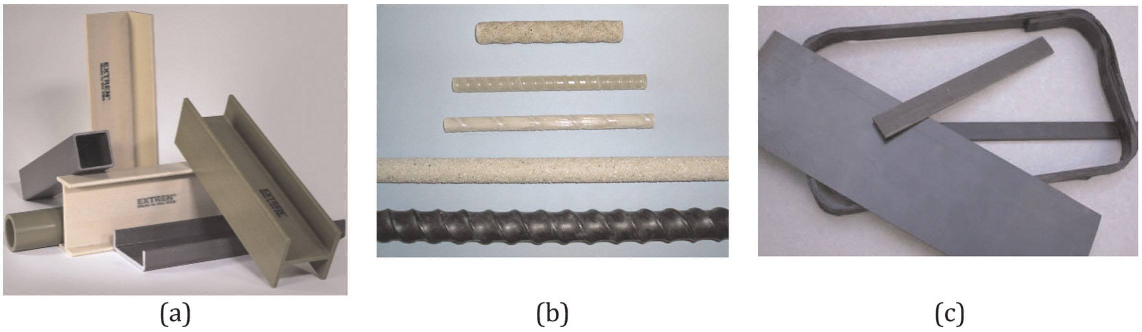


Figure 2.
Schematic diagram of pultrusion process (courtesy of Strongwell [24]).

bundles, mats and surfaces veils. Roving is the term used for glass fibre bundles and tows for carbon fibre bundles. The unidirectional rovings or tows provide strength and stiffness in the longitudinal direction. While the continuous filament or strand mat (CFM or CSM) and stitched or woven fabric provide strength in the transverse direction. Surface veils are also used for UV and corrosion protection. Pultruded parts are produced by impregnating dry fibres with resin and guiding them through a heated die (mould) and allowing them to cure. The cured material is then pulled through the die to give it the desired tensile strength. The part is cut at the end of the die to the required length [7, 8, 31, 32]. The pultruded products including FRP profiles, rebars, plates and strips are shown in **Figure 3**.

Pultruded FRP parts mainly use glass and carbon fibres in structural engineering applications. Glass fibres are more common due to their low cost. Use of aramid fibres is limited in pultrusion. Carbon fibres are used in FRP strengthening strips because of their high modulus. A pultruded FRP profile has a middle layer with unidirectional rovings and two outer layers with continuous filament mat (CFM)/chopped strand mat (CSM) or woven fabrics. Polyester surface veils are also added to outer layers for UV and corrosion protection. FRP profiles have 35–50% fibre volume, while FRP bars and strips have 50–60% fibre volume of the total volume [1, 8, 31, 32, 34]. The mechanical properties of typical FRP profiles are shown in **Table 2**. Comparison of steel and FRP bars in terms of tensile properties are given in **Table 3**. The properties of



(a) (b) (c)

Figure 3.
Pultruded FRP shapes, rebars and strips: (a) FRP structural profiles or shapes [24]; (b) FRP-reinforcing bars [33]; (c) FRP plates and strips [18].

Estimated fibre volume		**25–40%**	
Fibre architecture		**Roving and mat**	
Strength (MPa)	Tensile	Longitudinal	207–317
		Transverse	48–83
	Compressive	Longitudinal	207–359
		Transverse	110–138
	Shear	In-plane	31–48
		Out-of-plane	27–31
	Flexural	Longitudinal	207–338
		Transverse	69–131
	Bearing	Longitudinal	207–269
		Transverse	179–234
Modulus (GPa)	Tensile	Longitudinal	18–28
		Transverse	6–10
	Compressive	Longitudinal	18–26
		Transverse	7–13
	Shear	In-plane	3.0–3.4
	Flexural	Longitudinal	11–14
		Transverse	6–12
Poisson's ratio	Longitudinal		0.33–0.25

Table 2.
Mechanical properties of pultruded FRP wide-flanged profiles (glass-reinforced vinylester shapes 6–13 mm thick) [2, 6, 7].

Property	**Material**			
	Steel	**GFRP**	**CFRP**	**AFRP**
Density (kg/m^3)	7850	1750–2180	1430–1670	1300–1450
Longitudinal modulus (GPa)	200	35–60	100–580	40 -125
Longitudinal tensile strength (MPa)	450–700	450–1600	600–3500	1000–2500
Ultimate tensile strain (%)	5–20	1.2–3.7	0.5–1.7	1.9–4.4

Table 3.
Comparison of tensile properties of steel and FRP rebars (with volume fraction of fibres ranging from 50 to 75%) [18].

commercially produced FRP strengthening strips using glass and carbon fibres are shown **Table 4**.

2.2.2 Wet or hand layup

Wet or hand layup is a manual method for producing FRP strengthening sheets and fabrics. Typical properties of commercially produced FRP sheets and fabric are

	Standard-modulus carbon-reinf. Epoxy strip	High-modulus carbon-reinf. Epoxy strip	Glass-reinf. Epoxy strip	Carbon-reinf. Vinylester strip
Fibre volume (%)	65–70	65–70	65–70	60
Fibre architecture	Unidirectional	Unidirectional	Unidirectional	Unidirectional
Thickness (mm)	1.2–1.9	1.2	1.4–1.9	2.0
Width (mm)	50–100	50–100	50–100	16
Longitudinal modulus (GPa)	155–165	300	41	131
Longitudinal tensile strength (MPa)	2690–2800	1290	900	2070
Ultimate tensile strain (%)	1.8	*Not reported*	2.2	1.7

Table 4.
Typical properties of FRP strengthening strips [8].

	Standard modulus carbon fibre tow sheet	High-modulus carbon fibre tow sheet	Glass fibre unidirectional fabric	Carbon fibre multiaxial fabric
Fibre architecture	Unidirectional	Unidirectional	Unidirectional	Various
Thickness (mm)	0.165–0.330	0.165	0.356	*Not reported*
Width (mm)	600	600	1200	*Not reported*
Longitudinal modulus (GPa)	230	370	72	230
Longitudinal tensile strength (MPa)	550	510	220–470	508
Ultimate tensile strain (%)	1.67–1.7	0.94	2.1–4.5	1.7

Table 5.
Typical properties of FRP sheets and fabric strengthening materials [8].

given in **Table 5**. This method can be used in situ or offsite. Various fibres are stacked in the resin matrix and allowed to cure in the mould. The cured FRP part takes the shape of the mould. Due to high adhesive properties, epoxy resin is commonly used for strengthening applications with carbon or glass fibres. Some applications that employ hand layup, such as, FRP sandwich panels in bridges, require offsite fabrication. A method using prepregs is also a type of hand layup method. In this method, the resin is pre-impregnated onto the unidirectional fibres and partially cured in sheet-like products termed as prepregs. The prepregs are cut and placed in different orientation in a mould and allowed to cure in an autoclave. Many manufacturers produce prepregs for automotive and aerospace industries [8, 16].

3. FRP applications in civil engineering

FRP composites are used in various primary and secondary structural applications in buildings and bridges. All-FRP profiles and structures, FRP rebars and prestressing tendons, and FRP strengthening systems for existing structures are few of the most popular applications of FRP composites in civil engineering.

3.1 All-FRP structures using FRP profiles

Pultruded FRP profiles have been used in various all-FRP new structures and bridges. Where large single-component elements for bridges are required, resin transfer moulding (RTM), resin infusion moulding (RIM) and vacuum-assisted resin transfer moulding (VARTM) manufacturing processes are used. Here, the focus will mainly be on pultruded FRP shapes. Pultruded FRP profiles resemble structural steel sections, but their behaviour is more or less like timber structures [35]. Pultruded FRP profiles are produced as close or open sections. Some common sections include wide-flanged sections, I-sections, parallel flange channels, rectangular hollow sections, and square hollow sections. FRP shapes have been used in chemical and food processing plants, cooling towers, lightweight foot and road bridges, building systems, railway platforms, marine structures and structures where electromagnetic transparency is needed [36–42]. Chemical inertness, corrosion resistance, lightweight and low maintenance are the key drivers behind the use of FRP structural components. Electrical and magnetic non-conductivity of glass FRPs make them suitable for use in telecommunication and other electronic industry. Cooling tower industry has seen a major development in the use of FRP profiles. Several manufacturers [24–26] produce bespoke cooling tower FRP elements as well. University of Arizona Cooling Tower using custom-made glass FRPs and standard pultruded FRPs by Creative Composites [25] is shown in **Figure 4(a)**.

Multistorey frame commercial or residential buildings have not seen much growth in the use of standard pultruded FRP profiles. This is mainly due to difficulty in finding an efficient and economical way of joining FRP components in buildings. The current design practice uses steel-like joint detailing, which is not optimised for FRP frame joints. The first demountable and mobile prototype FRP multistorey office building named the Eyecatcher was constructed by Fiberline composites in 1999 (**Figure 4(b)**). This 15-m-tall five-storey building was showcased at the Swiss Building Fair in Basel, Switzerland. After the exhibition, the Eyecatcher building was relocated to another place in Basel, where it is still being used as an office building. The building had three adhesively bonded parallel trapezoidal FRP frames connected by wooden floor decks. Bolting was only employed where needed for dismantling the structure [8, 35, 44].

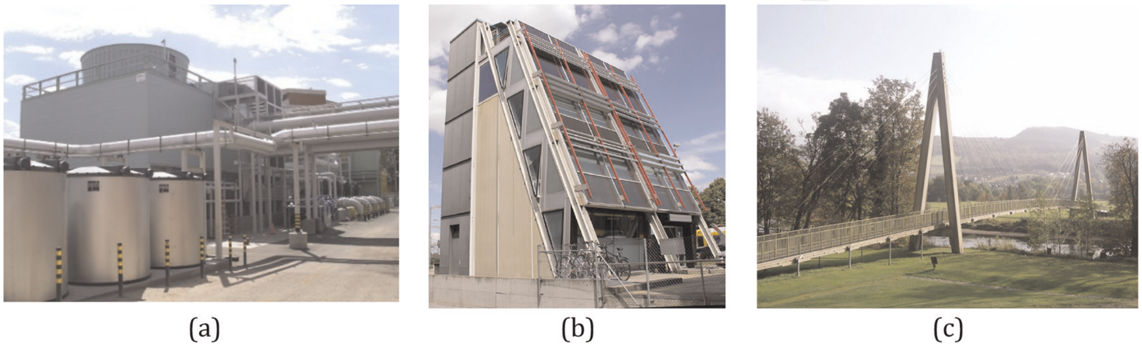

(a) (b) (c)

Figure 4.
All-FRP structures: (a) University of Arizona Cooling Tower using pultruded glass FRP [43]; (b) the eyecatcher five-storey FRP framed building Basel Switzerland [44]; (c) Aberfeldy Scotland footbridge [45].

FRPs have been used in bridges since 1970s. Fast deployability, corrosion and fatigue resistance, high strength-to-weight ratio and mouldability are some of main properties of FRPs making them suitable for bridges. FRP components, standard or custom-made, are used in bridge decks and superstructure. Aberfeldy cable-stayed bridge in Scotland is the world's first major FRP footbridge, completed in 1992 (**Figure 4(c)**). It carried pedestrians and golf buggies. Except concrete foundations, the entire superstructure was made up of FRP composites. The bridge was 113 m long having glass FRP decks supported by aramid FRP composite cables [8, 46–48]. This was followed by construction of the Bonds Mill Lift bridge near Gloucester, UK, in 1994, which was the world's first FRP composite road bridge. This bridge is constructed over a canal with a mechanical lifting mechanism for navigation purposes. It included a multicellular FRP box girder filled with structural foam. The aim of this filled girder was to resist the local bending from wheel loads [1, 46–49]. The other notable FRP composite bridges include no-name Creek bridge, Kensas, USA, in 1996 [49], Kolding Denmark FRP pedestrian bridge, 1997 [26, 50], Pontresina bridge Switzerland in 1997 [35], Dawlish rail footbridge Exeter UK in 2011 [51], and the Pont y Ddraig or the Dragons bridge at Rhyl Harbour, North Wales, built in 2013 [49, 52]. More details about FRP composite bridges can be found elsewhere [3].

3.2 FRP reinforcement for concrete members

FRP-reinforcing bars, grids and prestressing tendons are used in concrete members to reinforce or prestress concrete members. FRP-reinforcing bars have been used in construction since 1970s but gained popularity by late 1980s [8, 18]. There are many reasons for using FRP reinforcements in concrete. The main reason is superior durability of FRP rebars; and the other reasons include high strength, lightweight and electromagnetic neutrality of glass FRPs. Due to non-corrosiveness of FRP, it is likely to find structural applications in or near marine environments, and in chemical and industrial plants. Glass, carbon and aramid FRP rebars are commercially available. The mechanical properties of GFRP, CFRP and AFRP rebars are given in **Table 6**. FRP reinforcements perform well in internal and external aggressive environmental conditions that can affect durability of reinforced concrete members. These aggressive environmental factors include the influence of moisture, temperature, sustained stress, chlorides, alkali, UV actions, carbonation and acid. Detailed discussion on effects of these durability parameters on concrete members using various FRP rebars can be found in *fib* 40 [18].

Research in fibre-reinforced polymer rebars is very well developed. This is reflected in various specific design guides available for design of concrete structures using FRP bars in Europe and USA. The Task Group 5.1, formerly known as Task Group 9.3, is responsible for producing design guides for FRP reinforcements in concrete in the CEB-FIP Model Code design format. In 2007, the group produced the technical report '*fib* 40 – FRP reinforcement in RC structures' [18]. There are number of design guides produced in the USA as well, including 'ACI 440.1R-15: Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars' [33] and 'NCHRP research report 907: Design of Concrete Bridge Beams Prestressed with CFRP Systems' [53]. Recent research on FRP rebars, rods and cables is reported in the papers [54–56].

Property	**GFRP**	**CFRP**	**AFRP**
	E-glass/epoxy	**Carbon/epoxy**	**Kevlar 49/epoxy**
Fibre volume fraction	0.55	0.65	0.60
Density (kg/m^3)	2100	1600	1380
Longitudinal modulus (GPa)	39	177	87
Transverse modulus (GPa)	8.6	10.8	5.5
In-plane shear modulus (GPa)	3.8	7.6	2.2
Major Poisson's ratio	0.28	0.27	0.34
Minor Poisson's ratio	0.06	0.02	0.02
Longitudinal tensile strength (MPa)	1080	2860	1280
Transverse tensile strength (MPa)	39	49	30
In-plane shear strength (MPa)	89	83	49
Ultimate longitudinal tensile strain (%)	2.8	1.6	1.5
Ultimate transverse tensile strain (%)	0.5	0.5	0.5
Longitudinal compressive strength (MPa)	620	1875	335
Transverse compressive strength (MPa)	128	246	158

Table 6.
Mechanical properties of GFRP-, CFRP- and AFRP-reinforcing bars [18].

3.3 FRP strengthening systems

Externally bonded FRP systems have been used since the mid-1980s to strengthen and repair/retrofit exiting structures [57]. FRP sheets, plates, strips and fabrics can be used to strengthen or repair concrete, timber, steel and masonry structures [20]. Strengthening enhances the load-carrying capacity or ductility of the structures. While, retrofitting or repair restores the original strength or ductility of the deteriorated structure. However, the terms strengthening, repair and retrofitting have been used interchangeably in the past. The deterioration happens due to environmental factors, design errors, accidental events or lack of maintenance [8, 19].

The emphasis here is on FRP strengthening for concrete structures. The initial research on FRP strengthening for concrete structures happened in Europe and Japan in the 1980s. Externally bonded FRP systems were developed as an alternative approach to column jacketing and steel plate bonding to concrete members. Bonding steel plates to tensile zone of concrete beams increases its flexural strength. Steel plates can corrode resulting in a weaker bond between the plate and concrete member. Steel plates are heavy too and require heavy equipment for handling. On the other hand, FRP strengthening systems are lightweight and non-corrosive.

Researchers in Switzerland and Japan started developing FRP systems for flexural strengthening of bridges and concrete confinement of columns by around 1980s. Since then, significant research on FRP strengthening systems has been undertaken, especially in the last two decades. The development of design codes in Europe, Japan, Canada and the USA is ongoing [57]. Several design guides have been produced as a result. In the UK, The Concrete Society produced the 'Technical Report No. 55 on Design guidance for strengthening concrete structures using fibre composites' in 2012 [16]. In Europe 'CEB-FIP fib bulletin 14' [19] and in America 'ACI 440.2R-17' [57] are the design guides for externally bonded FRP strengthening systems. Other design guides for FRP strengthening systems in the USA, Japan and Italy are included elsewhere [58–66]. A comparison of various design guides for FRP strengthening is presented in [67].

FRP strengthening can be applied to concrete members using *wet layup*, *prepreg*, *precured* and *near-surface mounted (NSM)* systems. The *wet layup* system consists of dry unidirectional or multidirectional fibre sheets or fabrics impregnated with saturated resin. Both the resin infusion and curing take place onsite. The *prepreg* systems have partially cured fibre sheets or fabrics, pre-impregnated offsite. The prepreg system is fully cured onsite. The *precured* FRP systems, as the name suggests, are manufactured and cured offsite. An adhesive is used to bond these FRP systems to concrete members. The *NSM* FRP system consists of circular or rectangular bars or plates bonded into grooves made on the surface of concrete members. The mechanical properties of all FRP strengthening systems are affected by environmental factors, such as high temperature, chemical exposure and humidity. A reduction factor is usually applied to the mechanical properties of the FRP strengthening system to account for the environmental factors. Details of these reduction factors can be found in 'ACI 440.2R-17' guide for FRP strengthening system [57]. **Figure 5** shows various FRP strengthening systems in real structures. Qualitative comparison of FRP strengthening sheets using carbon, aramid and E-glass fibres is presented in **Table 7**. The criterion in this table is only applicable to strengthening applications of FRP.


(a) (b) (c) (d)

Figure 5.
FRP strengthening systems [68]: (a) column strengthened with woven unidirectional carbon fibre fabric; (b) CFRP plates and strips bonded to a bridge concrete beam; (c) externally bonded CFRP plates for flexural strengthening; (d) near-surface mounted (NSM) flexural strengthening of bridge decks with CFRP rods near negative moment regions.

Criterion	**Fibre composite sheet made up of:**		
	Carbon fibres	**Aramid fibres**	**E-glass fibres**
Tensile strength	Very good	Very good	Very good
Compressive strength	Very good	Inadequate	Good
Young's modulus	Very good	Good	Adequate
Long-term behaviour	Very good	Good	Adequate
Fatigue behaviour	Excellent	Good	Adequate
Bulk density	Good	Excellent	Adequate
Alkaline resistance	Very good	Good	Inadequate
Price	Adequate	Adequate	Very good

Table 7.
Qualitative comparison among high tensile—carbon, aramid and E-glass fibres in FRP strengthening application [69].

4. Durability aspects of FRP composites

Environmental factors affect durability performance of FRPs in terms of reduction in strength and stiffness. These environmental factors include moisture, ultraviolet exposure, elevated temperature, alkaline or acidic and saline solutions, freezing–thawing cycle and high humidity. Various testing and mitigation measures are available in the design guides [16, 18, 19, 33, 57] for FRP rebars and strengthening systems. The available testing for durability includes hot-wet cycling, alkaline immersion, freeze–thaw cycling, ultraviolet exposure, salt water and dry heat. Protective coatings can be applied to FRP composite part to account for various environmental factors. Carbon fibre is resistant to alkaline/acidic environment, whereas plain glass fibre degrades in these environments. In high alkaline and high moisture environments, carbon FRPs should be used in place of glass FRPs.

GFRP and AFRP are non-conductive (electrical insulators), while carbon FRP is conductive. Carbon-based FRP should not be used in direct contact with steel elements to avoid galvanic corrosion. CFRP composites are also resistant to creep rupture under sustained loading and fatigue failure under cyclic loading [33, 57]. Durability of externally bonded FRP composites in concrete structures is reviewed in a recent paper [70]. There is a lack of long-term durability and performance data for FRP profiles and their joints [71]. Durability of FRP composites exposed to elevated temperature and fire, ultraviolet radiation, creep and fatigue loads, freeze–thaw conditions and moist environment is discussed in a comprehensive book by Karbhari [72]. Structural health monitoring and field evaluation of FRP composites' durability are also explained in the book [72] and the recent review paper [73]. Ageing effects on mechanical properties of FRP are discussed in [74, 75].

5. Sustainability of FRP

Sustainability is about meeting the needs of the present without compromising on the needs of future generations, as per Brundtland report [76]. In the past, good structural design used materials and resources efficiently with focus on performance and economy. The sustainable design approach is based on material that considers environmental, economic and social factors and energy and resource consumption in addition to performance criteria. The evaluation of sustainability of materials involves life cycle assessment from cradle to grave including raw material procurement, fabrication and processing, construction, maintenance, recycling and disposal. An ideal sustainable material would have a closed life cycle that utilises renewable resources, energy and zero waste with low impact on environment, people and society [10].

Due to lightweight and ease in transportation, FRP composites are generally less energy-intensive to produce. FRPs also have minimal ecological and carbon footprint compared to the traditional materials. FRPs have no corrosion with superior performance in chemically aggressive environments. FRP composites resist creep and fatigue loads better than other materials. This leads to low maintenance for structures that use FRP materials. Resultantly, the expected durability of structures is enhanced by using FRPs. Sustainability of FRPs can be better understood by evaluating various stages of their lifespan and their impact on environment. In this way, better insights can be gained into the life cycle assessment of FRPs.

5.1 Lifespan of FRP composites

FRP composites are considered to have long lifespans. There are four different stages of FRP's lifespan: (1) extraction and production of FRP material; (2) manufacturing; (3) use and (4) end-of-life disposal.

5.1.1 Material extraction and production

The first stage involves sourcing raw materials for producing input materials for FRP composites. After extraction, the materials are processed and refined to become input materials for FRP manufacturing. The extraction and production of FRP input materials requires energy [6]. **Table 8** shows the energy intensity required for extraction and production of different materials. Thermosetting polymer resins are created through energy-intensive chemical process. Carbon fibres have relatively very high energy consumption compared with other synthetic fibres. Due to high energy demand, most pultruded FRP profiles use glass fibres rather than carbon fibres. Carbon fibres have far better strength though compared to conventional materials. The lightweight of FRPs reduces energy required for transportation at a later stage in their life cycle. The carbon emission due to transportation of traditional material is significantly higher than FRP composites. Using FRP composite as an alternative to steel reduces the weight of the structural component to about 60–80% [6, 77].

5.1.2 Manufacturing

While FRP composites have promising properties for structural engineering, their production on mass scale is yet to be realised. The main barriers to their widespread use include low production, lack of automation and high cost. The energy consumption of various manufacturing processes of FRP composites are shown in **Table 9**. The consumption is just for the manufacturing process, not for constituent materials. Manual methods, such as hand layup and prepreg, require significant energy compared to automatic processes, like pultrusion and filament winding. As FRP composite materials require more than two materials, additional energy may be needed for fibre impregnation, surface preparation, additives, fabrics and solvents. Pultrusion and filament winding have very low energy inputs of 3.1 and 2.7 MJ/kg [77], respectively.

Low energy intensity input materials and manufacturing combined with automation can reduce the cost of FRP composites significantly. Pultrusion process benefits

Material		Energy input (MJ/kg)
Polymers	Polyester resin	63–78
	Epoxy resin	76–80
Fibres	Glass fibre	13–32
	Carbon fibre	183–286
Metals	Steel	30–60
	Stainless steel	110–210
	Aluminium	196–257

Table 8.
Energy content for extraction and production of input materials [77].

Manufacturing process	Energy consumption (MJ/kg)
Pultrusion	3.1
Resin transfer moulding (RTM)	12.8
Vacuum-assisted resin infusion (VARI)	10.2
Filament winding	2.7
Hand/wet/spray layup	14.9
Injection moulding	19.0
Autoclave moulding	21.9
Prepreg	40

Table 9.
Energy consumption for manufacturing of FRP composites [77].

from low energy input, high production rates and automation. Even though pultrusion requires the least energy to produce FRP parts, it cannot produce very complicated shapes. Pultrusion is only limited to making very simple section profiles, such as tubes, wide-flanged sections, parallel flange channels, railings, poles and ladders [77]. Other energy-intensive processes like RTM, infusion moulding and prepreg are used to produce complex shapes. Single-component FRP bridge elements are usually manufactured by resin-infused/prepreg methods [48].

5.1.3 Use

FRP composites have been used in various industries, such as aerospace, automobile, construction, marine, consumer products and appliances. Especially, advanced FRP composites have been adopted well in aerospace industry. The Boeing 787 Dreamliner contains 80% of FRP composite materials by volume. The Airbus A380 is the first aircraft to have CFRP composite wing box. The boats have also been constructed from FRP composites. Today, 90% of the hulls of modern boats consist of FRP composites. In automotive industry, 90% of truck bodies are made of FRP composites. In these industries, the lightweight of FRP composites reduces fuel consumption and carbon emissions. In military applications, aramid fibre composites are used in bulletproof jackets and other impact resistant body outfits. Construction industry uses about a quarter of globally produced FRP [6, 77].

5.1.4 End-of-life disposal

Reuse of FRP composites for another application is a sustainable way to dispose of FRP waste. Ideally, FRP waste should be reused as FRP part in another application. However, due to special production and application of FRPs, reuse potential for FRP parts is very limited as compared to the traditional materials, such as steel and timber. FRP composites can be disposed of in three ways: dumping, incineration and reuse/recycling. *Dumping in landfill* is the cheapest way to dispose of FRPs. The scrap FRP composites must be sorted and separated. However, separating high value fibres from cured resins is difficult in FRP products, as steel and other parts might be attached to the FRP products [78].

5.2 Recycling of FRP composites

Thermoplastic-based FRP materials are easier to recycle by remelting and remoulding due to weaker molecular bonds in thermoplastic resin matrix. Thermoset-based FRP composites are difficult to recycle due to cross-linked nature of thermoset resins [79]. There are three main processes for recycling thermoset resin-based FRP waste materials: (1) incineration-with partial energy recovery from heating of the organic part and co-incineration-with both raw material and energy recovery; (2) thermal and chemical recycling-with decomposition processes to partially recover fibres and energy; (3) mechanical recycling-with breakdown of FRP composites by shredding, grinding and milling resulting in smaller fibrous or powdered products.

5.2.1 Incineration and co-incineration

Incineration and *co-incineration* are the methods of energy and/or material recovery for thermoset-based FRP materials. *Incineration* results in 'partial energy recovery from heat generated during combustion of the organic part'. While, *co-incineration* leads to recovery of both energy and raw material [79]. In incineration process, 50% of the waste remains as ash, which still needs to be landfilled. Air pollution resulting from incineration is one of the setbacks of incineration. Co-incineration has been tried in Germany to convert FRP waste into energy and clinker (the raw material) for cement manufacturing [80]. No ash is produced in this method, two-thirds of composite waste is converted into clinker and one-third is recovered as fuel for kiln. One drawback of co-incineration is that the composite waste material needs to be reduced to small particles suitable for cement kiln. Incineration and co-incineration can be classified as reuse methods.

5.2.2 Thermal recycling

Thermal recycling decomposes the FRP waste material into raw recovered fibre and results in partial energy recovery. It is only applied to CFRP composite waste, where the value of recovered fibre and energy is more than the cost of thermal recycling. It requires large amount of FRP material waste to justify the cost of recycling. The most common thermal recycling method is *pyrolysis.* It involves heating the FRP waste in an inert atmosphere to recover the polymer as oil. Another thermal recycling process is *oxidation in fluidised beds*. The resin matrix is combusted in a hot and oxygen-rich flow in this method resulting in fibre recovery. Strength and shape degradation may happen to the recovered fibres in thermal recycling. Thermal recycling is still far away from becoming commercially viable recycling process [79].

5.2.3 Chemical recycling

Chemical recycling consists of dissolving the resin using chemicals at low temperatures. This is a gentle thermal stress-free method. The recovered fibres retain their original strength in this process. Some limitations of this method include use of hazardous solvents, reduction in length of recovered fibres and lack of adhesion capacity of the recovered fibres. Like thermal recycling, chemical recycling is yet to become an economically viable solution. It is just limited to low-volume CFRP recycling [79].

5.2.4 Mechanical recycling

Among all methods, *mechanical recycling* is the most developed and viable process to recover reusable fibres [79]. This consists of shredding, grinding and milling the waste FRP material into smaller-sized filler material. The extracted materiel can either be used in new FRP products, which are based on bulk or sheet moulding processes or in concrete with cementitious, asphaltic or polymer binders [78]. The mechanical recycling has several economic and environmental benefits. These include no air pollution, no complicated and expensive equipment, and recycling ability on a larger scale. Some drawbacks consist of risk of ignition during shredding and low value recovered fibres. Carbon fibres can retain their strength though, while glass fibres lose their strength after thermal treatments [78, 79]. Use of glass and carbon FRP waste material in concrete and its life cycle assessment are presented in a recent paper by Singh et al. [74].

6. Conclusions

Research in use of FRP as rebars and strengthening systems is well developed with several design guides produced worldwide. There is a lack of legal design codes and awareness among structural engineers for FRP structural profiles and their joints. Some evolving design guides for pultruded FRP shapes have been produced in last two decades, such as Eurocomp design code [81], ASCE Pre-Standard for pultruded FRP [82], CIRIA C779 FRP bridges—guidance for designers [49] and Italian guide for pultruded FRP elements [83]. These guides are not legally binding for all-FRP structural design. Work is in progress in Europe and America for developing agreed design codes for all-FRP structures. Several automatic and manual manufacturing processes of FRPs were discussed. Pultrusion is the most cost-effective and eco-friendly process for producing constant cross-sectional FRP profiles at high production rates by means of automation.

The long-term durability and performance data for FRP profiles and their joints is limited. Some data is available, though, for FRP strengthening systems and rebars. Glass FRPs are by far the most common FRP composites with a market share of 90% of the FRP produced worldwide. Due to low viscosity, thermosetting resins (polyester, vinylester and epoxy) are the most popular polymer matrices for producing FRP structural products. The recycling methods for FRP including incineration, chemical, thermal and mechanical processes were discussed. Recycling of FRPs seems to be the most challenging aspect of sustainable design. Only a limited percentage of FRPs can be recycled, which may not be economically feasible keeping in mind the cost of recycling process.

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