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Review

The Mechanical and Environmental Performance of Fiber-Reinforced Polymers in Concrete Structures: Opportunities, Challenges and Future Directions

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Abstract: The construction sector is well known for its critical environmental impact resulting from the consumed amounts of raw materials and the tremendous emissions of greenhouse gases. Therefore, scientists need to promote and study the environmental implications of using alternative solutions such as fiber-reinforced polymers (FRP) throughout their service life. FRPs have gained increasing popularity in the last few years due to their durability, high corrosion resistance, light weight and high strength. Life cycle assessment is considered one of the most important methods to investigate the environmental impacts of the FRP. The aim of this paper is to present an overview of fiber-reinforced polymer composites in concrete structures with an investigation focusing on their environmental and mechanical properties in civil engineering structures. The main focus is set on the properties of fiber-reinforced polymers, their use as a strengthening technique in concrete structural members and their environmental impact using the life cycle assessment method. The reported results from the literature reveal that utilizing FRP composites in structural members instead of traditional materials improves their strength and stiffness and reduces environmental impacts.

Keywords: life cycle assessment (LCA); fiber-reinforced polymer (FRP); internal reinforcement; external reinforcement; mechanical properties of FRP; environmental impact of FRP

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1. Introduction

The construction industry is one of the most essential sectors in the world which contributes to the national economy and the development of the nations. In 2020, the industry contributed 26% to the global gross domestic product (GDP) [1]. However, despite its huge advantages, it was inevitable that the industry would end up at the center of concern for many scientists due to its direct impact on the environment, as it consumes 40% of global natural materials annually, accounts for 40% of energy consumption, is the reason for 25% of global waste, depletes 15% of freshwater resources and is responsible for 40% of greenhouse gas (GHG) emissions [2–4]. In addition to the negative environmental impacts, the deterioration of conventional structures over time and the high cost of maintenance underlines the necessity to look for new creative solutions to find new structures that need a lower maintenance cost, have a longer lifecycle, are more environmentally friendly and are more resistant to environmental conditions [5]. One possible approach can be achieved by utilizing more sustainable building materials such as fiber-reinforced polymer (FRP) composites as reinforcement or as a strengthening solution for construction instead of conventional materials. FRP composites, also called advanced polymer composites (APC), are essentially composed by using a polymer matrix consisting of a resin such as polyester, vinyl-ester and epoxy reinforced with different grades of basalt, aramid, carbon or glass fibers [6,7]. Furthermore, FRP composites have gained huge popularity in the civil engineering society in the past few years due to their advantageous features, such as their light weight compared to traditional steel, nonmagnetic characteristics, ease of use, non-corrosive nature, high specific strength-to-weight ratio compared to conventional materials and high specific stiffness [6–10]. Nevertheless, there are some limitations facing FRP composites that lie in their high cost, the fast loss of strength and stiffness at high temperatures, low ductility, low shear strength and the difficulties of bending available FRP rebars [11]. FRP composites are used in new projects on a full scale, whereas in other cases, they are used partially in rehabilitating an already existing structure (retrofitting, strengthening and repairing) [12,13]. FRPs are applied as internal reinforcement [14–16] such as rods, tendons and bars [17,18], or as external reinforcements [19–21], such as sheets, laminates and wraps [22,23], to improve the performance of both concrete and timber structures, whereas in other cases, FRPs are used for strengthening masonry walls [24]. Chopped fibers are also utilized to enhance the compressive strength of concrete and to improve the stabilization of soil by mixing the fibers with cement and then adding it to the soil [25]. The most common types of FRP composites used in construction are carbon-fiber-reinforced polymer (CFRP), aramid-fiber-reinforced polymer (AFRP), glass-fiber-reinforced polymer (GFRP) and basalt-fiber-reinforced polymer (BFRP) [26].

The main advantages of CFRP are its high tensile strength and high elastic modulus compared to other types of FRPs, which reduce the deformations in the CFRP reinforced elements [27,28]. GFRP is mainly the most commonly applied reinforcing fiber for polymeric matrix composites [29], owing to its relatively low cost in contrast to other types of FRPs and its high tensile strength compared to conventional steel. Nonetheless, its modulus of elasticity is four to five times lower in GFRP compared to traditional steel, which increases deformations in GFRP reinforced elements [22,30].

Furthermore, the corrosion resistance, durability, lightweight and economic benefits of FRP through the lifecycle of construction help them to decrease the consumption of energy and greenhouse gas (GHG) emissions, accompanied by the processes of maintenance, transportation, installation and production. Moreover, growing concerns over global warming and the depletion of natural resources have made fiber-reinforced polymers (FRPs) a good alternative to conventional building materials and have raised the need to study environmental impacts which are associated with the use of FRPs in structures [7]. One of the designed tools to describe and evaluate the environmental impacts of a product throughout its lifecycle stages is the life cycle assessment (LCA) method [31]. LCA is defined according to the ISO 14040:2006 standard as "the compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle" [32]. LCA looks at the product's life, including the extraction of raw materials (cradle), production, use, recycling and the final disposal of the product (grave). The framework of LCA usually comprises four fundamental steps, which are the goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation process [33]. The flow chart of the LCA, including the inputs and output flows of materials, energy and pollutants, is described in Figure 1. Many life cycle assessment studies have been developed to describe the environmental impacts of FRP used in structural elements, as can be found in the literature [34–38].

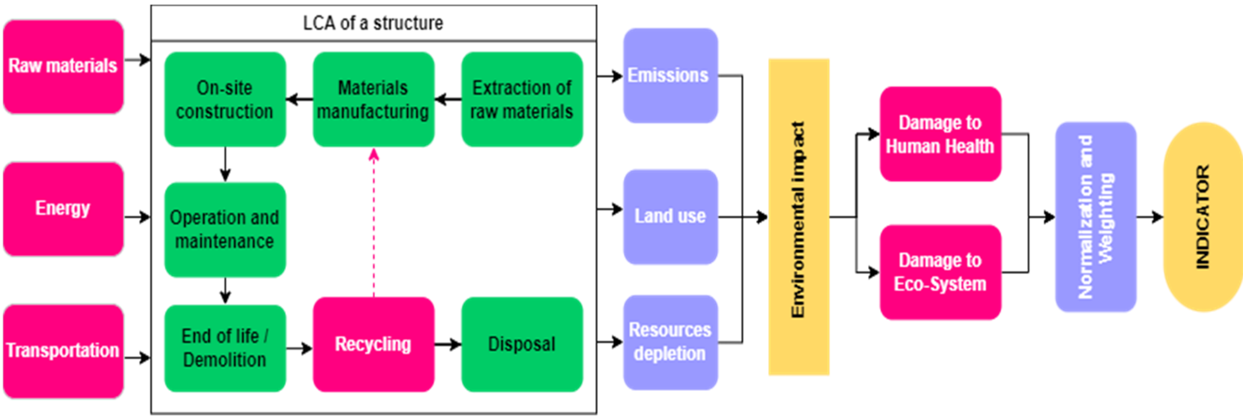


Figure 1. Flow chart of the LCA, including input and output flows of materials, energy and pollutants from a life cycle perspective.

1.1. FRP Composite Production Techniques

There are four common techniques to produce FRP composites [39,40]. (1) The pultrusion technique is used to manufacture FRP composites by producing a continuous length of structural shapes with the same cross-section. The process involves applying resin baths to the rolled FRP material and heating and curing the FRP material to become a solid composite. (2) The hand lay-up molding technique [41] is used in the field for the fabrication and repair of FRP sheets by placing a resin layer on the RC member, and then another layer of pre-cured FRP sheet is placed on top of the resin layer. The pre-cured FRP sheet is then covered by another layer of resin, resulting in a sandwich FRP composite. (3) The vacuum-assisted resin transfer molding (VARTM) technique works by infusing the resin into the FRP reinforcement. The curing of the FRP composite is completed while it is under vacuum. It is worth mentioning that the VARTM technique allows for more versatile geometries compared to the pultrusion technique. (4) The automated wet lay-up manufacturing process utilizes a robotic arm to produce the desired length of FRP bars. The process consists of impregnating the fibers in a polymeric resin, which is then shaped by the robotic arm. It is believed that the automated wet lay-up is cost effective because of the reduction in human involvement, and the production technique is simple.

1.2. Aim and Scope

The use of FRPs in construction is relatively new compared to the use of traditional materials. Many researchers have investigated the mechanical properties of FRP and their use in construction, but a few of them have evaluated the environmental impact of using FRP composites, which is why this paper aims to combine them both by providing a sufficient review of the mechanical and the environmental performance of fiber-reinforced polymers in concrete structures. The mechanical performance section focuses on the mechanical properties of FRPs, and it also focuses on strengthening reinforced concrete beams and columns by using FRP composites. The environmental performance section investigates the environmental impact of FRPs used in structural elements through life cycle assessment.

This review is organized into five sections. The introduction (Section 1) provides general ideas about FRPs, the advantages and disadvantages of FRPs, the use of FRPs in construction and the aim of the paper. The methods and the stages used to collect the relevant literature, including the inclusion and exclusion criteria, are mentioned in Section 2. The mechanical and physical properties of FRPs, the production of FRPs and the strengthening of RC beams and columns using FRP components are mentioned in Section 3. The environmental impact of FRPs through LCA, the environmental performance of FRP in beams and bridges and the waste management for FRPs are evaluated in Section 4. The conclusions and the directions for future research are presented in Section 5.

2. Research Methods

Fiber-reinforced polymer composites are used in different fields and domains. The use of FRPs in construction can be traced to the 1970s, when semi-load-bearing and infill panels were made of GFRP and used in construction [42]. The first pedestrian bridge made totally from FRP was constructed in Tel Aviv in 1975 [43], and the first FRP bridge constructed on a public highway is in Oxfordshire, UK. The construction work of the bridge was completed by 2002 [42,43]. The following stages were used to establish the literature of interest. In stage 1, a comprehensive search was organized using Google Scholar, ResearchGate, Science Direct and Scopus. The subsequent combinations of keywords {life AND cycle AND assessment AND fiber AND reinforced AND polymer} or {fiber AND reinforced AND polymer AND concrete AND structures} were searched across all fields in published papers. The chosen sources were limited to peer-reviewed literature such as journal papers, review papers and conference proceedings. Other sources were included in exceptional cases such as websites and books. Another filtering process was implemented in stage 2 by checking keywords, titles and abstracts. Any paper that did not address the LCA of FRP, the mechanical performance of FRP or the strengthening of structural elements using FRP as its main focus was excluded from the search. In stage 3, the full papers were examined and read thoroughly to determine their suitability for inclusion in the review. These stages are illustrated in Figure 2.

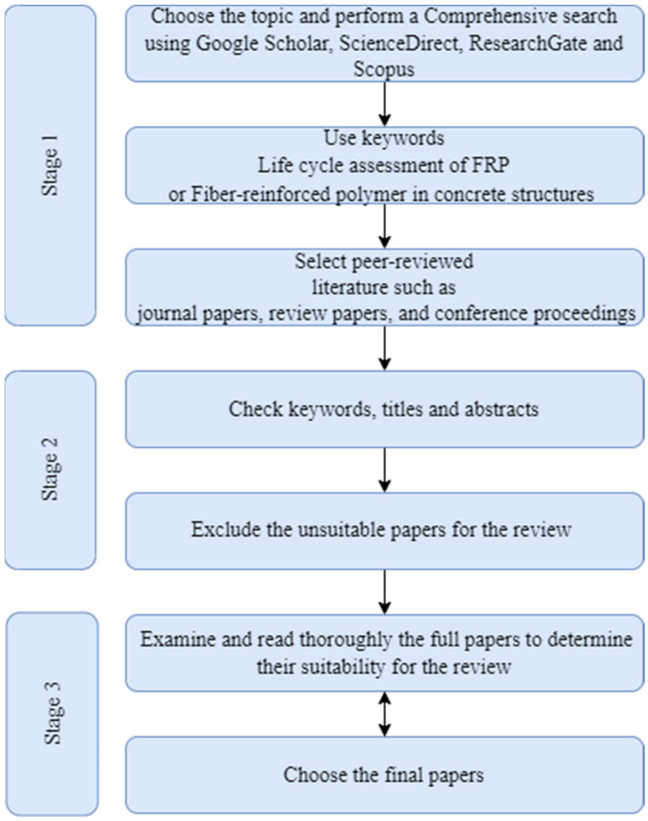
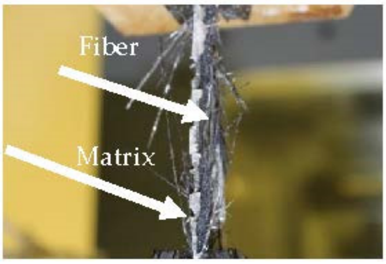


Figure 2. Research methodology.

3. Materials and Mechanical Behavior of FRPs

There are two main applications of FRP composites implemented in the construction industry: (a) the strengthening of existing RC members using FRP sheets, which consists of a reinforcement material (e.g., carbon, glass, aramid, etc.) covered in a matrix, as illustrated in Figure 3a, and (b) FRP reinforcement bars, which are used as internal reinforcement for (RC) structural members, as shown in Figure 3b.



(a)

(b)

Figure 3. FRP materials: (**a**) FRP sheets (**b**) Basalt fiber bars.

3.1. Mechanical Behavior of FRP Composites

The advantageous use of FRP composite reinforcement over steel across different areas, such as its superior mechanical properties, cost, durability and its resistance to corrosion, has made FRP composites become popular in the construction industry. The mechanical behavior of different FRP composites has been reported for both FRP sheets and FRP bars. This paper focuses on four FRP composites, namely carbon (CFRP), glass (GFRP), basalt (BFRP) and armid (AFRP).

3.1.1. CFRP Composites

Carbon fibers are characterized by having a high deformation modulus similar to steel, a high fatigue strength and the ability to not absorb water [44]. Carbon fibers have diameters in the range of 5 to 10 µm, and when manufactured, using the pultrusion technique to produce CFRP bars, it possesses an extremely high tensile strength. The mechanical properties of CFRP bars, including the density, tensile strength, deformation modulus, elongation, coefficient of thermal expansion and Poisson's ratio, are depicted in Table 1. Although CFRP bars can offer a 40–60% reduction in mass compared to conventional steel, the manufacturing cost is between 1.5–10 times when the material and processing costs are considered [45].

Table 1. Typical FRP mechanical properties [9,44,46].

Type of FRP (Trade Name)	Density kg/m^3	Tensile Strength MPa	Modulus of Elasticity GPa	Elongation%	Coefficient of Thermal Expansion (10–6/°C)	Poisson's Ratio
Carbon Fibers						
Carbon	1700	3700	250	1.2	−0.6 up to −0.2	0.20
Carbon (high modulus)	1950	2500–4000	350–800	0.5	−1.2 up to −0.1	0.20
Carbon (high strength)	1750	4800	240	1.1	−0.6 up to −0.2	0.20
Aramid Fibers						
Aramid (Kevlar 29)	1440	2760	62	4.4	−2.0 longitudinal 59 radial	0.35
Aramid (Kevlar 49)	1440	3620	124	2.2	−2.0 longitudinal 59 radial	0.35
Aramid (Kevlar 149)	1440	3450	175	1.4	−2.0 longitudinal 59 radial	0.35
Aramid (Technora H)	1390	3000	70	4.4	−2.0 longitudinal 59 radial	0.35
Aramid (SVM)	1430	3800–4200	130	3.5	n/a	n/a
Basalt Fibers						
Basalt (Albarrie)	2800	4840	89	3.1	8.0	n/a
Basalt (Rockbar)	1750	1000	50	2.24	2.0	n/a
Basalt (BCR)	1800	1100	70	2.20	0.35–0.592	n/a
Basalt (Composite rebar)	1900	>900	40	1.8	9–12	n/a
Glass Fibers						
Glass (V-rod) Glass (Aslan) Glass (Nefmac)	1250–2500	710 690 600	46.4 40.8 30	1.2–5.0	6–10	n/a

3.1.2. GFRP Composites

GFRP bars are the most commonly used due to their cost effectiveness when compared to all other FRP fabrics. However, the mechanical properties of GFRP bars are known to have a comparatively low deformation modulus, low alkaline resistance, low humidity and low long-term strength due to stress rupture [47].

3.1.3. BFRP Composites

The applications of BFRP fibers have been being extensively researched over the last decade. BFRP fibers possess excellent mechanical properties and durability characteristics. Furthermore, they have high resistance to high temperatures, corrosion, radiation and UV exposure [48].

3.1.4. AFRP Composites

The use of AFRP composite bars is limited due to their low long-term strength, their sensitivity to UV radiations and the difficulty of cutting and processing the composite. However, AFRP fibers have excellent impact resistance [49].

3.1.5. Matrix of FRPs

The fibers are combined with a matrix that consists of resins and other additives to produce the composite bars and sheets. There are two main types of resins. (a) Thermoplastic resin: It is a resin that can be affected by temperature to become softer or harder. (b) Thermosetting resin: It is produced by irreversible hardening of a soft viscous fluid by means of curing and/or radiation [50]. The thermosetting resin is the most common, as it is not affected by temperature after hardening. Table 2 presents the physical and mechanical properties of three of the most commonly used thermosetting resins, namely polyester, epoxy and vinyl-ester resins.

Table 2. Typical matrix of FRP materials [50].

Properties	**Thermosetting Resins**		
	Polyesters	**Epoxy**	**Vinyl-Ester**
Density, kg/m^3	1200–1400	1200–1400	1150–1350
Tensile strength, MPa	34.5–104	55–130	73–81
Deformation modulus, GPa	2.1–3.45	2.75–4.10	3.0–3.5
Poisson's ratio	0.35–0.39	0.38–0.40	0.36–0.39
Coefficient of thermal expansion, 10–6/°C	55–100	45–65	50–75
Saturation, %	0.15–0.6	0.08–0.15	0.14–1.30

3.2. Strengthening of RC Beams Using FRP Composites

FRP composite sheets are used in strengthening the application of RC structural members. There are different strengthening techniques and patterns that can be used for the shear and flexural strengthening of beams using externally bonded FRP materials.

Strengthening Patterns

There are different strengthening techniques and patterns that can be used for the shear and flexural strengthening of beams using externally bonded FRP materials, which can be on the plane of the beam cross-section [51]. The strengthening pattern can be either discontinuous or continuous [52]. In the case of continuous wrapping, the moisture migration should be taken into consideration. There are three main configurations of installing FRPs to the cross-section of the beam using the wet layup technique, which is as shown in Figure 4:

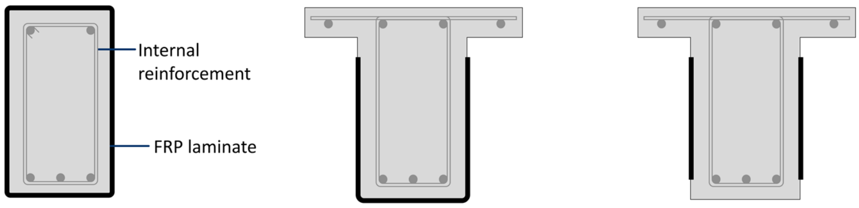


Figure 4. Different FRP wrapping schemes.

- Fully wrapped;
- Wrapped on three sides (U-wrap);
- Two-sided FRP strips.

The most efficient pattern is the first one, as there is a greater bond length and confinement to the cross-section of the member, followed by U-wrapping and the two-sided FRP strips.

3.3. Anchorage System for Shear

There are few guidelines regarding the installation of FRP anchors. ACI 440.2R-08 specifies the design guidelines for the shear strengthening of beams using externally bonded CFRP. It has been found that the anchor layout, the anchor hole inclination from the axis perpendicular to the surface, the depth of the anchor hole, the area of the anchor hole, the anchor hole chamfer radius, the amount of CFRP materials in the anchors, the anchor fan length, the anchor fan angle and the anchor reinforcement are factors affecting the anchorage [53].

3.4. Failure Modes

There are different types of failure modes in FRP composites. The most common failure modes are the debonding of the FRP material, concrete separation and the rupture of the fabric, as illustrated in Figure 5.

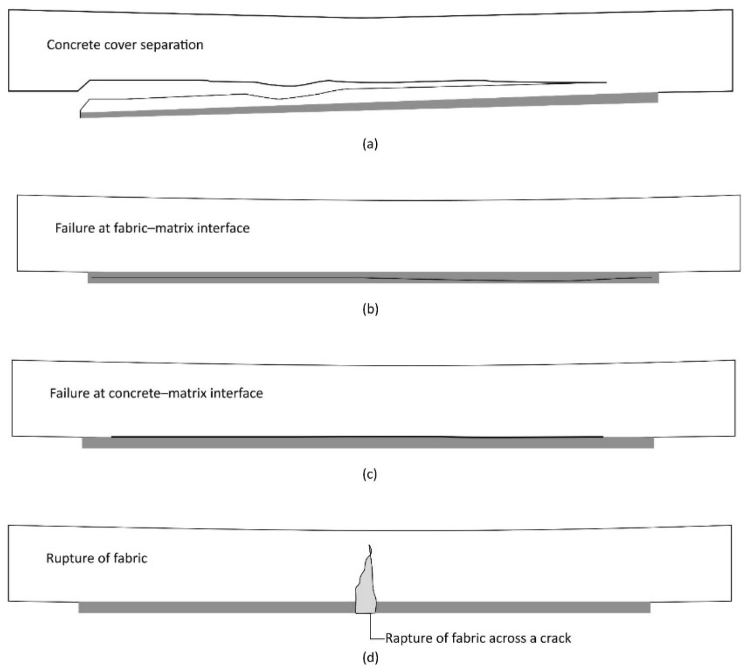


Figure 5. Illustration of failure modes.

3.4.1. Concrete Separation

The failure of concrete separation happens if the top and/or bottom of the beams experiences longitudinal cracks that are sequenced to expand the number of the shear cracks on the shear span, resulting in the failure of the beams. Then, the lateral layer of concrete separates. This has been reported in different studies. The reason behind this type of failure is the enhanced bond characteristics between the FRP and concrete substrate [54,55].

3.4.2. Debonding of FRP

Although there are several modes of failure, the debonding failure mode is the most common mode of failure for the strengthened beams with the FRP system. This type is recognized clearly by a transverse crack that starts near the loading point, then increases toward the unloaded areas [56].

3.5. Beam Strengthening in Shear

FRP materials are used in the shear, flexural and torsional strengthening and the rehabilitation of RC beams to improve their capacity in resisting the applied forces. Shear strengthening must be undertaken when the flexural capacity is higher than the shear capacity after the flexural strengthening of the beam. An effective design method for shear strengthening is when the principal fiber direction is placed in a way that is parallel to the maximum principal tensile force, which is generally roughly around 45 degrees to the horizontal axis of the member. However, for practicality, the fibers are preferably attached perpendicular to the axis of the member [57]. In the work by Baggio et al. (2014) [58], beams were cast with dimensions of 150 mm wide by 350 mm deep, which were strengthened with glass-fiber-reinforced polymer (GFRP) and carbon-fiber-reinforced polymer (CFRP) with and without anchors using a U-wrap scheme. The configuration of the wrapping scheme is illustrated in Figure 6, as the authors studied the effects of full-depth and partial-depth FRP U-wrap. In this study, it was noted that a 50% increase in shear capacity over the control beam was due to the use of full-depth GFRP with no anchors. However, the beams strengthened with partial-depth GFRP experienced a 52% and 36% increase in the shear capacity of the beam with and without anchors, respectively. On the other hand, beams strengthened with CFRP sheets with and without anchors showed a 67% and 75% increase in shear capacity over the control beam, respectively, with both beams exhibiting a ductile flexural failure mode.

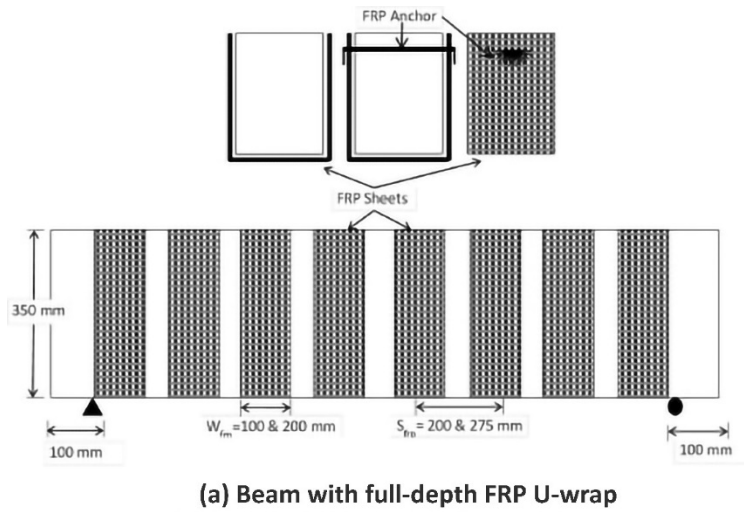


Figure 6. *Cont.*

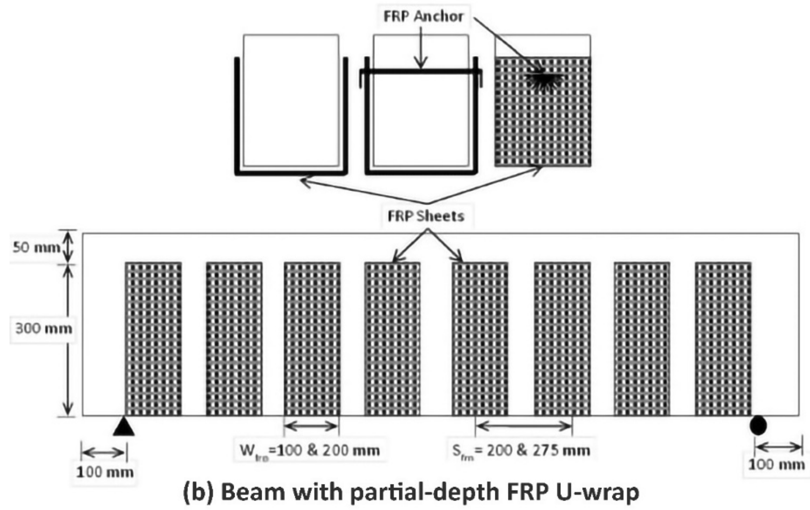


Figure 6. Shear strengthening using a U-wrap scheme [58].

The shear strengthening using CFRP with a U-wrap scheme was investigated [59]. The spacing between the fibers was the parameter to be changed. The dimensions of the casted beams were 120 mm wide by 300 mm in depth, with a length of 2000 mm. Epoxy Sikadur-41 and Sikadur-31 CF were used. The configuration of the wrapping scheme is shown in Figure 7. The failure modes experienced are summarized in Figure 8. It is noted that the U-wraps were only activated by 22%, where the fiber experienced debonding failure from the concrete beam.

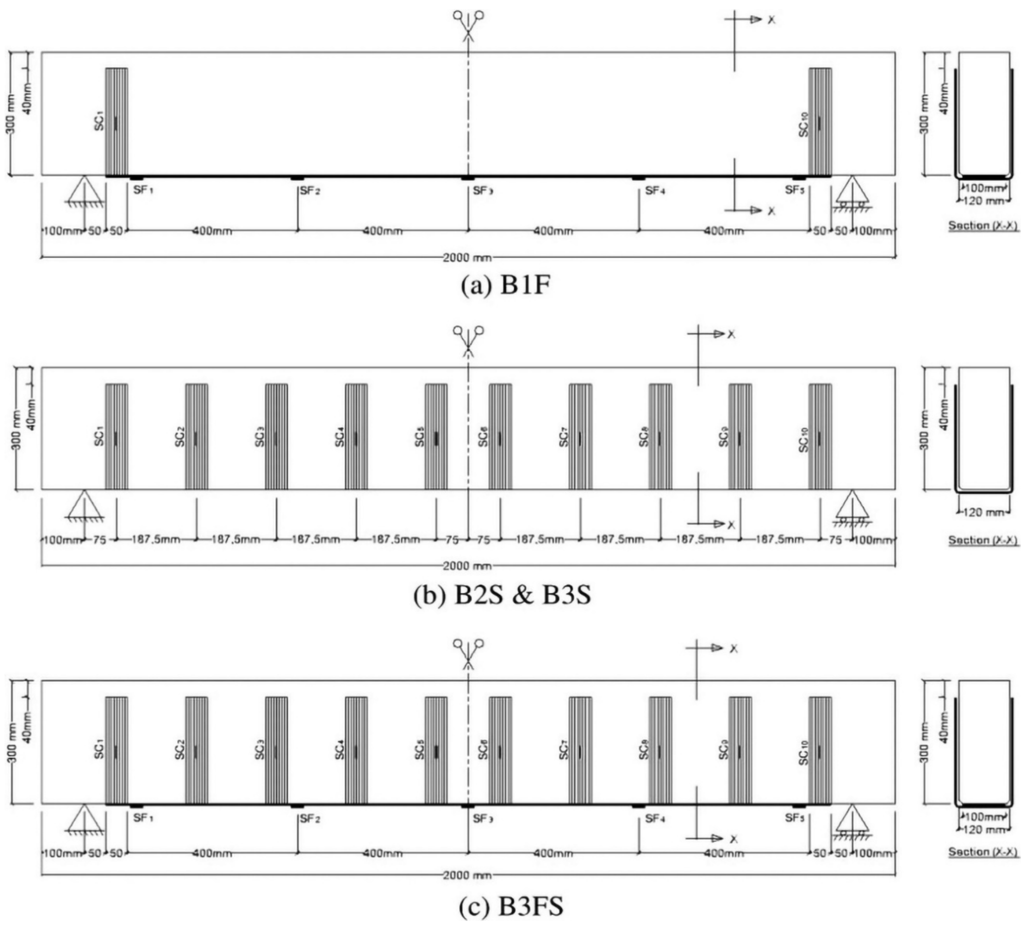


Figure 7. Wrapping scheme for shear strengthening [59].

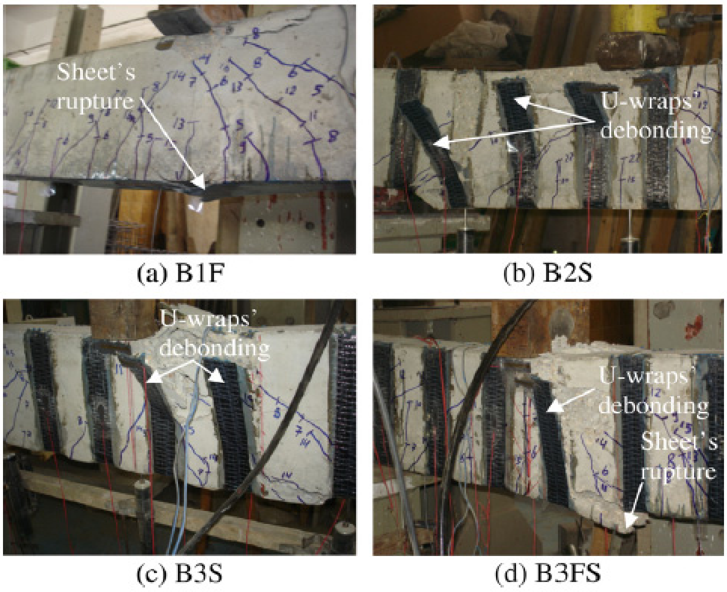


Figure 8. Failure modes experienced [59].

3.6. Beam Strengthening in Flexure

Some researchers conducted their studies on CRFPs in the flexural strengthening of beams [59–63], and others focused on BFRP [64], GFRP [65] and Jute FRPs (JFRP). Moreover, some researchers used two types of FRPs, such as the authors of [66] and [67]. In all experiments, beam dimensions varied in widths of 100–200 mm and in depths of 150–300 mm, with a compressive strength of concrete of 35–50 MPa. The FRP thicknesses that were used varied between 0.12 mm and 0.275 mm. Two types of flexural tests were used: the three-point loading test and the four-point loading test. All specimens were equipped with a linear variable distance transducer (LVDT) to measure the deflection.

For control beams, researchers recorded that the main failure mode was a flexural failure with huge vertical cracks, which was the crushing of beams in the compression with the steel yielding in tension. For beams strengthened with one layer of an FRP sheet or more than one layer, the failure mode was the debonding of the FRP sheet, either from the end or the midspan [63,65]. Moreover, different failure modes were recorded for different wrapping schemes used by researchers.

The results obtained by Spadea et al. (2015) [60] showed that beams with only CFRP laminates that were bonded to the tension side carried more loads of about 30% compared to the control specimen; however, the failure mode was brittle as expected where the capacity dropped with the CFRP debonding. CFRP laminates with anchorage systems showed more ductile failure with a larger increase in the load-carrying capacity.

Chen et al. (2018) [64] used different strengthening schemes with BFRP strengthening and compared the results. These schemes were longitudinal strips at the tension side, U-jacketing as an anchorage, inclined U-jacketing at 45° and U-jacketing at the midspan only. The ultimate load for the longitudinal strips was 74.37 kN, which was 20.63% more than the control specimen, and the debonding strain was 0.96%, which was higher than the debonding strain of 0.2% of CFRP recorded by Fu et al. (2017) [68]. They concluded that the failure mode can be changed from FRP debonding to FRP rupturing by using a U-jacketing scheme. Moreover, the inclined U-jacketing scheme is more effective than the vertical scheme, where the increase in the load-carrying capacity was increased by 55.2% for the inclined scheme and 37.7% for the vertical scheme.

In other research, the authors of [66] studied the strengthening of normal and retrofitted beams using CFRP for flexural strengthening and GFRP for shear–flexural strengthening with different strengthening arrangements. All failure modes for different beams were recorded. The control beam followed a bending failure, which is a typical one for an un-strengthened beam. However, beams strengthened with CFRP had a delayed crack appearance, with crack widths less than those of the control beam. The two main failure modes for strengthened beams were the debonding and snapping of the CFRP sheet. Regarding the load-carrying capacity, strengthened beams with one and two layers of CFRP showed an increase of about 22% and a decrease in deflection of about 39% compared to the control beam. Moreover, the results showed that a higher concrete cover does not increase the load-carrying capacity. The strengthening was also very effective in increasing the bending capacity for preloaded beams with pre-cracks. The flexural capacity of beams and deformability can be increased significantly with the addition of extra layers.

El-Ghandour (2011) [59] studied using CFRP for strengthening beams with different steel ratios for shear and flexure, tested using a three-point bending test. Beams were strengthened using U-wraps and longitudinal sheets. Results showed that, although 33.3% of the cracking load was increased, the efficiency of flexural strengthening was reduced by 65.7% in capacity, and stiffness was reduced at high shear damage. On the other hand, for high flexural damage, the U-wrap capacity efficiency was reduced by 38.3%; however, the failure mode changed to be more ductile failure at a strain of 0.01.

Ceroni (2010) [61] also studied the CFRP strengthening of beams using FRP laminates and near-surface-mounted (NSM) bars under cyclic and monotonic loads. The beams were divided into two groups: low steel reinforcement percentage (1%) beams and high steel reinforcement percentage beams (1.5%). Under a monotonic load, FRP laminates increased load carrying capacity by around 26% to 50% for the 1% reinforced steel beams and 17% to 33% for the 1.5% reinforced steel beams. The ductility for these beams was reduced because of the brittle failure mode caused by the debonding of the end sides of the FRPs. On the other hand, NSM bars had better results both in terms of ductility and failure mode. The failure mode for NSM bars was mainly concrete crushing in compression in addition to the concrete cover separation. Regarding beams tested under cyclic loads, beams strengthened with CFRP laminates showed at least a 10% reduction in debonding strength compared to the equal beams tested under monotonic loads. These results were also the same for [63], where the load-carrying capacity for an NSM CRFP-strengthened beam was higher than that of the EBR technique. This is mainly because NSM strips have a double bonding area when compared with EBR strips.

Mechanically Fastened and Externally Bonded Reinforcements (MF-EBR) were introduced for the first time by the authors of [62]. The new technique combines epoxy bonds from the EBR technique and fasteners from the MF-FRP technique, as shown in Figure 9. Multi-directional CFRP laminates were used for flexural strengthening in MF-EBR, and two types of loading were used, which were monotonic and fatigue loading. The results of MF-EBR were compared with those of the NSM and EBR techniques. An increase in the load-carrying capacity of about 37%, 86% and 87% was achieved for EBR, NSM and MF-EBR-strengthened beams tested under monotonic loads. The most interesting thing about MF-EBR was the ductility enhancement, which was measured using a normalized deflection capacity, and it showed almost double the value of that of the NSM technique. However, when tested under fatigue loading, the NSM technique showed the highest increase in the load-carrying capacity and a normalized deflection capacity compared to EBR and MF-EBR.

The effect of different FRP thicknesses on flexural behavior using hybrid-bonded (HB) FRP-strengthened beams was investigated by the authors of [69]. It was found that HB strengthening increased both ductility and load carrying capacity. Moreover, it was found that, as FRP thickness increased, three different things resulted, which were load-carrying capacity increasing when the FRP rupture was the controlling failure mode, the flexural stiffness within the elastic range increasing and the failure mode switching to fastener detachment. The authors concluded that the HB strengthening technique ensures the simultaneous occurrence of FRP rupturing and fastener detachment, which yields a good load-carrying capacity and the best ductility.

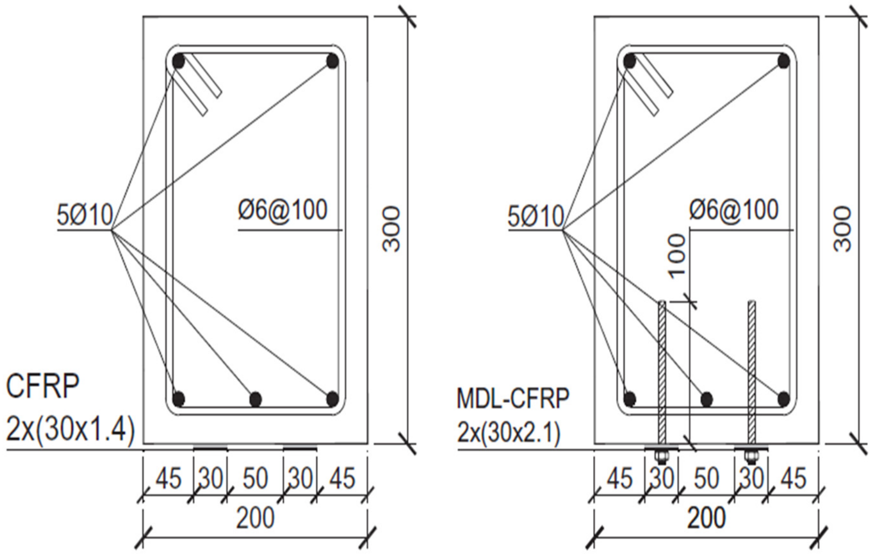


Figure 9. Cross-section of EBR and MF-EBR [62].

Using different laying patterns and layers of GFRP was studied by the authors of [65]. It was found that, for all laying patterns, the load-carrying capacity increased as the number of layers increased. Moreover, the failure mode tended to be more brittle as the number of layers increased. The best laying pattern was found to be a half U-wrap (bottom of the beam and half of both sides) with two layers, which had the best performance in increasing the flexural strength, economy and failure pattern compared to the other strengthened beams.

JFRP was used in beam strengthening and was compared with GFRP and CFRP [67]. The effect of flexural strengthening, failure mode and ductility were studied. All beams were strengthened in the same manner, which was one layer of either a full U-wrap along the whole beam length or strip wrapping. Results indicated that the flexural strength was increased by 62.5%, 125% and 150% for JFRP, GFRP and CFRP, respectively, for the full U-wrap, and by 25%, 37.5% and 50% for strip wrapping. Although JFRP showed lower flexural increasing values than the other FRP types, JFRP showed the highest deformability index, which proves that JFRP can be used as a strengthening material. Table 3 shows the summary of the results of strengthened beams.

Table 3. Summary table of strengthened beams.

Ref.	Beam Description	FRP Type	Strengthened Focus	Strengthening Scheme	Ultimate Load (kN)	Deflection (mm)	Failure Mode	Anchors
[60]	A1.1 A3.1	CFRP	Flexure	CFRP laminates to the tension side	86.8 74.8	78.9 61.6	Debonding of CFRP sheets (total and sudden loss of load capacity)	-
[70]	B150A B150B B150C B150D	BFRP	Flexure Flexure Flexure Flexure	BFRP laminates to the tension side U-wrap as anchorage Inclined U-wrap at 45° U-wrap at the midspan only	74.37 84.90 95.68 82.26	18.5 37.56 22.9 19.41	FRP debonding FRP rupture Compressive failure Cover separation	- - - -
[66]	CR3 CR5	CFRP	Flexural	CFRP laminates	93.66 121.7	13.61 16.31	Flexural debonding and snapping of CFRP sheet	U-strips at the ends only
[66]	SR2	GFRP	Shear	U-wrap as anchorage	146.20	16.55	Flexural failure	-
[59]	B1F B3FS	CFRP	Flexure Shear	FRP laminates FRP laminates and U-wrap	170 155	- -	Flexural failure Combined flexure–shear	-
[61]	A5 A9	CFRP CFRP	Flexure Flexure	FRP laminates NSM	44.7 45.9	- -	FRP tensile fracture Cover detachment	-
[63]	B-S-4 B-N-2-2	CFRP CFRP	Flexure Flexure	CFRP laminates NSM	94.57 91.57	13.21 24.5	Debonding Debonding	- -
[62]	EBR MF-EBR NSM	CFRP CFRP CFRP	Flexure Flexure Flexure	CFRP laminates - NSM	108.4 148.2 147.3	- - -	Debonding Bearing Rip-off	- Yes -
[69]	EB-1-0 HB-1-3	FRP	Flexure Flexure	FRP laminates Hybrid bond (HB) FRP method	51.58 54.88	19.85 26.99	Debonding FRP rapture	- -
[65]	BT11 BT12 BT21 BT23	GFRP GFRP GFRP GFRP	Flexure–shear Flexure–shear Flexure–shear Flexure–shear	Bottom and 25 cm of both sides Bottom and 25 cm of both sides Bottom and half of both sides Bottom and half of both sides	5.6% Mu resistance increase 43.2% Mu resistance increase 61.0% Mu resistance increase 140.0% Mu resistance increase	- - - -	Ductile failure Ductile failure Ductile failure Brittle failure	- - - -

Table 3. *Cont.*

Ref.	Beam Description	FRP Type	Strengthened Focus	Strengthening Scheme	Ultimate Load (kN)	Deflection (mm)	Failure Mode	Anchors
[67]	Beam 1	JFRP	Flexure–shear	U-wrap for full length	130	23.211	Ductile failure (huge deflection)	-
	Beam 2	CFRP	Flexure–shear	U-wrap for full length	200	16.31	Brittle failure	-
	Beam 3	GFRP	Flexure–shear	U-wrap for full length	180	17.62	Brittle failure	-
[58]	Beam1-Control	-	-	-	223	8.8	Shear	-
	Beam 2	CFRP	Shear	U-wrap	373	11.4	Flexural	-
	Beam 3	CFRP	Shear	U-wrap	390	16.9	Flexural	Yes
	Beam 6	GFRP	Shear	U-wrap	334	13.7	Shear debonding	-
	Beam 7	GFRP	Shear	PD- U-wrap	305	12.0	Shear debonding	-
	Beam 9	GFRP	Shear	PD- U-wrap	339	13.7	Shear compression	Yes
[66]	SR1	-		U-wrap	11.49	4.70	Flexural	-
	SR3	CFRP sheets	Flexure–shear	U-wrap	187.12	12.13	CFRP snapping and flexural failure	-
	SR4	CFRP sheets	Flexure–shear	U-wrap	187.74	12.40	CFRP debonding and shear failure	-
	SR5	CFRP sheets	Flexure–shear	L-Shaped	158.49	16.92	CFRP debonding and flexural failure.	-
	SR6	-	Flexure–shear	L-Shaped	115.81	8.55	CFRP snapping and flexural failure	-
	SR7	CFRP sheets	Flexure–shear	L-Shaped	193.35	16.12	CFRP debonding and flexural failure.	-

3.7. Strengthening of RC Columns Using FRP

3.7.1. Wrapped Concrete Columns with FRP

Concrete columns (CC) can fail if the lateral strain reaches its maximum capacity and if the concrete cover begins to crack followed by the steel reinforcement buckling [71]. Therefore, delaying the lateral strain of the CC from reaching its maximum capacity can lead to a CC performance enhancement. This can be achieved by wrapping the CC around its diameter with FRP, which produces lateral pressure on the diameter of the column. Confinement theory depends on maintaining fiber orientation in a transverse direction to the column [72–74]. The reason behind this theory is the lateral expansion that occurs due to the axial load. This lateral expansion causes tensile stresses in the confinement material, which leads to confining pressure on the CC lateral direction [75] The following sections discuss the effects of wrapping FRP on the CC behavior by considering the influence of factors of several parameters on the confinement degree.

3.7.2. Advantages of Wrapped Concrete Columns with FRP

Confining concrete columns mitigates the possibility of failure due to the unexpected load due to an earthquake or other load type, because the confinement of concrete columns with FRP materials increases the capacity of the member and its ultimate strain. Moreover, FRP-confined material acts as a permanent formwork and a non-corrosive reinforcement that protects the CC from aggressive environments. Additionally, Qasrawi et al. [76] mentioned that the localized damage is decreased when using FRP-confined CCs compared to the conventional RCC under blast loading, which can save civilians and properties regarding accidental or intentional explosions.

3.7.3. Different Parameters Affecting the Confinement of RC Columns

The confinement of concrete columns with FRP improves the strain and axial strength capacities of the member by a certain degree, which depends on different parameters such as cross-section shape, slenderness ratio, concrete strength, the method used in manufacturing the tube, fiber properties, fiber orientation and the thickness of the FRP [77].

3.7.4. Slenderness Ratio

The effect of slenderness on the axial performance of high strength [78] and normal strength concrete [79] wrapped with FRP circular tubes has been studied in the past. It was concluded that the enhancements degree of strain and strength capacities was decreased when increasing the slenderness ratio. Moreover, it was found that circular reinforced concrete columns wrapped by FRP material have lower significance in slender columns than in short columns [80–82].

3.7.5. The Shape of Concrete Columns

It was reported by Fam et al. [83], Hong and Kim [72], Pessiki et al. [84] and Mirmiran et al. [85] that the effect of FRP confining on non-circular columns behavior is less than that in circular cross-sections. Their results have verified that confining non-circular columns with FRP is not very effective, which is similar to confining circular columns because of the bending at the outward direction on the flat sides in non-circular FRP tubes. Ozbakkaloglu and Xie [86] have provided the same conclusion after conducting tests on circular and square FRP specimens filled by geopolymer concrete with the application of axial compression. Therefore, to overcome this problem, two methods were followed by researchers to improve rectangular and square concrete confinement columns, which were transforming the cross-section into circular and elliptical sections, respectively. The first technique was prefabricating FRP shells and placing them around the original concrete column and then filling the entire volume with concrete; therefore, the shape became circular, as shown in Figure 10a. A wet lay-up technique was used to fix FRP shells as sheets or strips [87]. The second method, illustrated in Figure 10b, was modifying the cross-section without creating a gap in the original concrete cross-section by using precast concrete segments [88].

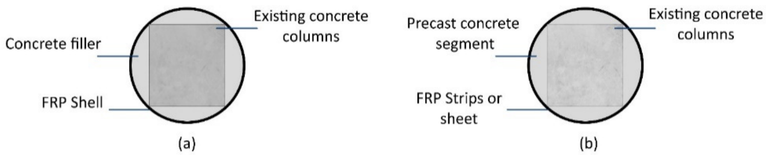


Figure 10. Transformation methods of non-circular columns: (**a**) placing prefabricated FRP shells and (**b**) using precast concrete segments.

Beddiar et al. [77] modified the first technique by gathering three sheets of GFRP that were made of twill weave glass, which had structural bending in order to transform the square CC cross-section, and then by filling the gap by shrinkage reimbursing cement mortar, as shown in Figure 11. Test results confirmed that the non-circular concrete column capacities of ductility and strength can be improved by using cross-section transformations.

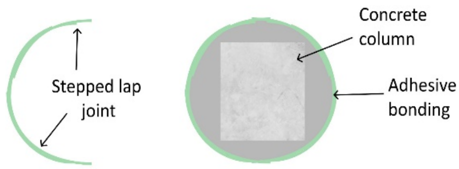


Figure 11. Modifying square concrete columns by using GFRP shell stepped lap joint.

Bhowmik et al. [89] evolved the second method for rectangular concrete columns with a high ratio. They formed capsule-shaped columns using rectangular concrete columns on the structural response.

3.7.6. Concrete Strength and Types

Vincent and Ozbakkaloglu [90] used different concrete, strengths, which were 35 MPa (N/mm^2), 65 MPa and 100 MPa, in order to find the concrete strength influence on the FRP CC behavior subjected to axial compression. They tested a total of 55 cylindrical samples with dimensions of a 305 mm height and a 152 mm diameter and subjected them to axial load. Tube-encased concrete and the wrapping of CFRP were used. Their research indicates that high and very high concrete strength sample ductility can be modified when using FRP confinement at a sufficient level. In contrast, when using the same ratio of confinement, the decrease in the compressive strength of concrete increases the strength and strain enhancements. This is because of the concrete properties in which the brittleness increases in concrete, and compressive strength is increased, which results in increasing the FRP confined material hoop rupture strain with decreasing the unconfined concrete strength. Therefore, confined concrete by an FRP material and having low compressive strength provides higher improvements in concrete capacity when capering it with a high and very high concrete strength wrapped by the same area of the FRP material. It has been clarified that the reduction factor of the strain does not have a significantly impact because of the different ways of making the FRP confinement, which are the FRP-tube and FRP-wrapped methods, and there are some deviations in the strength of concrete. This aspect is further supported by the research of Ozbakkloglu and Lim [91], who have mentioned that the reduction factor of the hoop rupture strain is reduced when increasing either the unconfined concrete compressive strength or FRP material elastic modulus.

3.7.7. Orientation of Fiber Effects

Further studies have been made upon the ones made by Kim et al. [73] and Hong and Kim [72]. These further studies have been conducted by Vincent and Ozbakkaloglu [74], who examined the effect of the orientation of fiber on confined concrete samples' axial behavior in the FRP tube. They prepared various tube types using the technique of filament winding with CFRP oriented at different angles aligned with the axial direction as the reference. The research concluded that the axial performance of the confined samples is impacted by the orientation of the fiber, and this effect is the maximum when the FRPs are oriented with the hoop direction. If there are more FRP materials at the hoop direction, the restraint in the lateral concrete dilation is provided. This happens because of the provided confinement by the FRP materials, which increases the confined concrete compressive strength and ultimately enhances the column axial capacity.

3.7.8. Stress–Strain Behavior of FRP

The strain can be divided into two main types. One is the ultimate strain ε_{fu}, and the other is the effective ultimate strain ε_{fe}. The effective ultimate strain has been found to be much less than the ultimate strain as a result of conducting experiments and determining the strain until jacket rupture [92]. Both strains are related to each other, and the ratio between them is mostly termed as the strain efficiency factor $k_s = \varepsilon_f e/\varepsilon_{fu}$. In order to find the tensile behavior of the FRP, two different tests can be made to characterize the tensile behavior of FRP, which are: flat coupon tensile testing [93,94] and split desk test specimens [95]. It has been noted that the split desk test gives lower values of ultimate strain compared to split desk test specimens, and that is because of the FRP ring circumferential bending at the two half disks gap and the discontinuities of the geometry at the ends of the FRP. Flat coupon tests are widely used, and most of the time, the data that are provided by the manufacturers comes from this test [96]. The possible reasons regarding the difference between the effective ultimate strain and ultimate strain have been indicated as follows: the tri-axial state of jacket stress, execution quality, reinforcement curved shape and local stress concentrations at the concrete core due to the inhomogeneous deformation, cracking and the size effects when using multiple layers.

Mirmiran et al. [97] tested 45 Carbon-Reinforced-Polymers (CFRP) of 6 × 12 in. cylindrical columns. These columns were examined in uniaxial compression. Two batches were considered for these columns: high and normal-strength concrete. They were covered by a different number of CFRP layers that varied from one to five layers. The Finite Element Method (FEM) model was followed using the Drucker–Prager approach, which defines concrete stress. Results indicated that the concrete strain behavior dilation rate depends on concrete strength and the number of layers. Moreover, it was mentioned that decreasing the number of layers increases the rate of dilation, and increasing the concrete strength decreases the dilation rate. It was also shown that the hoop rupture strain of the wrap is less than the reported strain by the uniaxial tensile coupon test, and the bond between the wrap and concrete does not have an impact on the confinement behavior significantly.

Toutanji [98] conducted experiments on glass-fiber-reinforced polymers (GFRP) and CFRP applied on cylindrical reinforced concrete columns, which were loaded with an axial force. Lateral and axial strains were recorded. Then, using the recorded strains, the ductility, stiffness, strain–stress behavior and ultimate strength were evaluated. The obtained ultimate strains of GFRP and CFRP were compared with the unwrapped reinforced concrete columns, and it was clearly noted that there was an increase of 100% to 200% in the ultimate strains in some of the confined specimens.

Researchers have conducted many tests on column specimens over the past years in order to come up with a fixed range of the effective ultimate strain. However, the dispersion in the results found between researchers is very large [99]. The following are examples of the results that were found. Xiao and Wu [100] indicated that the values of the effective ultimate strain are approximate 50–80%, obtained by flat coupons. However, De Lorenzis and Tepfers [101] stated that the strain efficiency factor varies from around 1.00 to 0.10 based on multiple reviews of FRP-wrapped circular samples. Similarly, Sadeghian and Fam [102] observed values ranging between 1.22 and 0.12 by forming a database that contains 454 cylindrical test tubes and analyzing them. Moreover, other authors [103,104] have also found similar averaged values, which were around 0.60, by conducting their own tests or by collecting data from the tests in the literature. However, it has been highlighted that effective ultimate strain does not have a specific range to be considered due to the high dispersion of the results. Therefore, it is recommended to perform tests to obtain the effective ultimate strain or strain efficiency factor of the desired FRP in wrapped applications. These tests results show the need for further investigations to predict a specific range of the ε_{fe} and how it is hard to produce a fixed number or small range.

3.7.9. Axial Loads on FRP Columns

Axial loads and bending moments are two important factors to consider regarding columns. The axial load is usually the load that come from the slabs and beams to columns, and in most cases, it is the compression force. Irshidat, Al-Saleh and Al-Shoubaki [105] studied the strengthening adequacy of carbon fiber/epoxy-composite-wrapped RC utilizing carbon nanotubes (CNTs) and focused on the axial load. A total of 14 rectangular cross-section RC columns were constructed for testing. The results of the experiment showed that utilizing CNT-modified epoxy resin enhanced the wrapped columns' toughness and axial load carrying capacity by 19% and 12%. Moreover, the CNT-enriched sizing agent (SCNTE) gave an axial carrying capacity of columns of 15% more than neat epoxy (NE) specimens, as shown in Table 4. It showed strong bonding between the fiber and concrete, which made the increasing capacity of the columns reasonable. High temperatures have been classified as one of the most unwanted environments for RC structures. Exposing RC columns to high temperatures commonly causes harmful effects such as concrete retrogradation, strength reduction and spalling. Irshidat and Al-Saleh [106] investigated the effect of CNTs on the axial load capacity of heat-damaged RC columns rehabilitated with carbon-fiber-reinforced polymer (CFRP) composites. Columns were cased for testing and were cured for 28 days. Thereafter, the samples were revealed to high temperatures of 500 and 600 degrees Celsius for two hours utilizing an electrical oven. Then, the damaged columns were rehabilitated utilizing the CNT-modified composites. The axial load test was applied, and the results showed that the columns were damaged by heat and were rehabilitated with CFRP (NE-500 and NE-600). Their axial load capacity was increased by 31% and 10% compared to the unrepaired columns (control) heated at 500 and 600 degrees Celsius.

Table 4. Comparison of different types of epoxy.

Reference	Specimen	Ultimate Load (KN)	Ultimate Displacement (mm)	Toughness (KN mm)	Failure Mode
[105]	Control	565	0.613	201	Brittle
	NE	633	1.207	564	Ductile/buckling
	CNTE	702	1.282	670	Ductile/buckling
	SNE	696	0.557	205	Sheet rupture
	SCNTE	729	1.245	506	Sheet rupture

Improving a model to forecast the hollow FRP composite column axial strength with buckling impacts is considered more economical than carrying out comprehensive testing. The domestic and worldwide pultruded I-section of FRP wide flange buckling was investigated by Barbero and Tomblin [107]. They proposed design equations based on their experimental results, which, in researchers' opinions, have been performing effectively to forecast the intermediate length critical loads of FRP-I section columns. GangaRao and Blandford [108] utilized different methods to predict FRP column axial strength by utilizing a model of strain energy density, which utilized the zone below the curve of the column axial stress–strain. Exploring the global buckling and local effects on the pultruded GFRP compression member strength was the main objective of their research. A total of 46 hollow-box-shaped columns were tested. The hollow box column results showed that the variance between experimental and predicted values differed from 8% to 19%.

3.7.10. Experimental Findings

The experimental findings investigated by the authors of [92,105,109] are presented in Tables 5–7. The ε_{fe} effective ultimate strain is less than the strain of tensile rupture, which is determined from the flat coupon test (ε_{fu} = 1.78%), as shown in Table 5. Moreover, the $k\varepsilon$ strain efficiency factor ranged from 0.48 to 0.77, and the mean value was k_ε = 0.60. However, this result coincides with what is proposed for TR55 for circular cross-sections and which, in general, is shown in other guidelines, regardless of being square cross-section columns. As shown in Table 6. It has been reported before that, according to the type of material, a better compressive axial capacity for Carbon FRP compared to Glass FRP is expected. However, results showing better results for strain values for glass materials is logical, because if the stress increases, the strain decreases. In other words, the element is more brittle or less ductile, which is the case of carbon. Table 7. proves that experimental results can be trusted, as the differences between the software and experimental work is low. Moreover, it also proves the opposite, which is that the software is working fine and the results from the software are accurate; thus, it can be used to design elements with FRP materials.

Table 5. Stress–strain results.

Reference	Cross-Section	f_{cc} [MPa]	f_{cc}/f_{co}	ε_{cc} [%]	ε_{fe}	$k_\varepsilon = \varepsilon_{fe}/\varepsilon_{fu}$
[92]	Square 150 × 150 mm	43.0	1.05	0.0069	−0.0097	0.55
		52.0	1.27	0.0091	−0.0116	0.65
		55.2	1.30	0.0139	−0.0088	0.50
		76.0	1.85	0.0197	−0.0119	0.67
		78.6	1.92	0.0182	−0.0109	0.61
		93.6	2.28	0.0145	−0.0110	0.62

Table 6. Compressive strength increment and wrapped specimen maximum axial strain, compared to unwrapped ones.

Reference	Cross-Section	Wrap Type	CFRP		GFRP	
			Compressive Strength (%) Increment	Maximum Axial Strain (%) Increment	Compressive Strength (%) Increment	Maximum Axial Strain (%) Increment
[109]	Circular (Dia. 508 mm)	Full (2 layers)	34	347	10	443
		Partial (4 layers)	32	355	8	580
		Full (7 layers)	17	1470	3	1860
	Rectangle (635 × 318 m)	Full (2 layers)	8	643	0.8	905
	Square (324 × 324)	Full (2 layers)	61	295	37	480
		Partial (4 layers)	53.8	75	27	315

Table 7. Difference between software and experimental results for maximum axial strain and compressive strength.

Reference	Cross-Section	Wrap Type	Results from the Laboratory		Software Results		Difference (Laboratory Software)	
			Compressive Strength (MPa)	Maximum Strain (mm/mm)	Compressive Strength (MPa)	Maximum Strain (mm/mm)	Compressive Strength (%)	Maximum Strain (%)
[109]	Circular (Dia. 508 mm)	Full (2 layers)	37.0	1.19×10^{-2}	38.85	1.34×10^{-2}	+5.0	+12.6
		Partial (4 layers)	39.0	1.41×10^{-2}	38.50	1.38×10^{-2}	−1.3	−2.1
	Rectangle (635 × 318 mm)	Full (7 layers)	30.5	2.11×10^{-2}	29.35	2.35×10^{-2}	−3.8	+11.4
		Full (2 layers)	23.8	9.83×10^{-3}	25.95	1.11×10^{-2}	+9.0	+12.9
	Square (324 × 324)	Full (2 layers)	34.1	9.23×10^{-3}	32.90	8.35×10^{-3}	−3.5	−9.5
		Partial (4 layers)	31.1	3.10×10^{-3}	31.60	3.70×10^{-3}	+1.6	+19.4

4. Environmental Performance of FRP

In the past few years and as a result of growing environmental problems such as climate change, global warming and the depletion of natural resources, it has become essential to investigate the environmental impacts of new products, especially products that have a long service lifetime compared to others such as FRPs, green concrete and steel. Fiber-reinforced polymers prove to be a more sustainable and environmentally friendly material compared to traditional materials due to their durability and corrosion resistance. An LCA study was conducted by the authors of [36], in which a comparison was made between BFRP-reinforced bars with steel and non-corrosive bars. It was found that BFRP rebars had the lowest environmental impact across the studied eighteen midpoint categories compared to steel, galvanized steel, GFRP and stainless steel. The global warming potential for BFRP rebars scored 74%, 49%,44% and 88% less than steel, galvanized steel, GFRP rebars and stainless steel respectively. In another study performed by the authors of [110], the environmental impact of GFRP was assessed by comparing it to traditional steel rebar at the production stage. It was reported that the overall environmental impacts of GFRP are higher than steel in most of the categories, particularly for fossil fuels, respiratory inorganics and climate change. In the same study [110], it was stated that the environmental impacts resulting from GFRP rebars compared to steel have less damage on the environment and human health when 1/8 of the weight of steel rebars is used. The environmental performances of the most used FRP components, such as carbon fiber, glass fiber, polyester resin and epoxy resin, were evaluated by the authors of [111] through LCA methodology. The results show that the negative environmental influence of glass fibers is less than that of carbon fibers in categories such as global warming potential (GWP), human toxicity (HTPC) and ozone depletion potential (ODP) by approximately 90%, 97% and 93% respectively, and the negative environmental influence of glass fibers is higher than that of carbon fibers in resource depletion (RP) category by 91%. It was also found by the authors of [111] that polyester resin has a smaller environmental impact in contrast to epoxy resin in categories such as GWP, ODP and RP by approximately 63%, 99.85% and 90%, even though the environmental impact on human toxicity (HTPC) category for polyester resin is almost seven times higher than that of epoxy resin. The human health impact through LCA for three different resin mixes of FRP composite materials was investigated by the authors of [112]. The results reveal that the materials have small environmental impacts, especially for the carcinogen, respiratory organics and respiratory inorganic impact categories due to the marginal toxicity levels in North American pultrusion factories. The authors of [113] compared multiple designs for a quay wall made from different materials such as GFRP, wood, steel and concrete regarding CO_2 emissions per kg material, and they applied LCA methodology. The results show that the wooden retaining wall has the lowest CO_2 emissions compared to the GFRP sandwich panel, which has the highest CO_2 emissions. It was also concluded that the sustainability of materials is not only dependent on the emissions per kg of material, but it also depends on the best use of the material in the right application.

4.1. Life Cycle Assessment of FRP Used in Beams

Modern structural elements should achieve a reduction in environmental impact accompanied by improvements in functional performance. In the past few years, fiber-reinforced polymers have shown favorable characteristics in terms of durability [114], and they have proved to be promising materials that can be used in various applications of civil engineering as a replacement for traditional materials, such as steel. The dominant materials in construction are concrete and steel, which are the most used materials in the world after drinking water [115]; however, the usage of these materials causes extra amounts of CO_2 emissions into the environment, the drastic depletion of resources and climate change due to global warming. Several scholars have used different strategies to minimize the environmental load caused by traditional materials to enhance the environmental performance of structural members.

An LCA study was conducted by the authors of [116] for different concrete beams to investigate the environmental impact of adopting BFRP bars as reinforcements instead of steel bars. The resulting values point to the fact that using BFRP bars as reinforcement instead of steel bars in concrete beams achieved significantly better performances across all eighteen environmental indicators evaluated in the study. Climate change emissions (CC), ozone depletion (OD), human toxicity (HT) and freshwater eutrophication (FE) were reduced by 38%, 40%, 78% and 85%, respectively, which makes BFRP a green solution for concrete compared to traditional steel. The authors of [34] performed an LCA study for three beams with the same span and under the same load in a marine environment. CFRP/GFRP-bar-reinforced seawater and sea sand concrete (SWSSC) beams were compared to steel-bar-reinforced common concrete (SRC) beams. It was found that the CFRP-SWSSC beams achieved a better environmental performance than the SRC beam in categories such as climate change (CC), terrestrial acidification (TA), human toxicity (HT) and particular matter formation (FPMF), with reductions of 29%, 37%, 1% and 40%, respectively. GFRP-SWSSC beams performed better than SRC beams in categories such as climate change (CC), terrestrial acidification (TA), ozone depletion (SOD), freshwater eco-toxicity (FRET), human toxicity (HT) and particulate matter formation (FPMF), with reduction rates of approximately 26%, 16%, 1%, 5%, 2% and 21%, respectively. An analytical study was conducted by the authors of [35] to evaluate the environmental impacts of CFRP, BFRP and GFRP rebars, and they compared them to conventional steel rebars in reinforced concrete beams. The LCA results concluded that GFRP, CFRP and BFRP-reinforced beams experienced fewer CO_2 emissions of 43%, 39% and 40% and less energy consumption by 47%, 32% and 50%, respectively, compared to steel-reinforced beams. A different study by the authors of [36] investigated the sustainability of BFRP and steel reinforcement in beams through LCA. The results of this study indicate that BFRP-reinforced beams scored improvements in all eighteen environmental impact categories compared to steel-reinforced beams, accomplishing a 7% and 21% reduction in global warming (GWP) and human carcinogenic toxicity (HCT). The environmental efficiency of basalt fiber reinforcement was studied in different ratios by the authors of [117] and was compared to the broadly used steel fibers in T-beams with the help of LCA. The presented results from this study for mixtures containing 1.5% and 0.5% fiber reinforcement at the midpoint and endpoint level show that basalt fibers have a better environmental performance than steel fibers. The 1.5% steel fibers exhibited an increase in environmental load compared to all other options. When the 0.5% steel-fiber-reinforced mixture was used, categories such as ozone layer depletion (OLD), aquatic ecotoxicity (AE), land occupation (LO) and terrestrial ecotoxicity (TE) favored the steel fibers over the basalt fibers. A comparative LCA study was made by the authors of [118] for strengthening reinforced concrete beams by using CFRP laminates instead of demolishing and rebuilding. It was reported from the study that the strengthening technique consumes less energy and reduces CO_2 emissions compared to the demolishing and rebuilding process. Furthermore, the authors of [119] conducted an environmental assessment through LCA for CFRP strips used as a strengthening reinforcement compared to the demolition and rebuilding of RC beams. The results of the study were in favor of the CFRP strip strengthening technique over the demolition and the reconstruction of the beams, where a reduction in the environmental impact was reported in the studied categories, which were global warming (GWP), human toxicity (HTPC) and ozone depletion potential (ODP). An environmental assessment through LCA by the authors of [120] was used to evaluate the energy consumption of concrete beams strengthened with a different solution of CFRP or BFRP sheets. The study shows that the CFRP solution consumes more energy than the BFRP strengthening solution due to the high embodied energy for the CFRP. The authors of [121] performed an LCA study to determine whether the reuse of an existing structural element shear strengthened with unidirectional glass or carbon fiber fabric can lead to a lower environmental impact compared to the case of demolishing and rebuilding the structural element. The authors reported an approximate 76% and 68% reduction in CO_2 emissions when beams were shear strengthened with GFRP or CFRP, respectively, in comparison to the CO_2 emissions resulting from demolishing and rebuilding the structural element. Furthermore, ozone depletion (ODP) was also reduced by approximately 14% when GFRP and CFRP were used for shear strengthening. Moreover, the authors of [122] investigated the environmental impact of GFRP fabric-strengthening solution used on a timber beam by applying the LCA methodology. The results indicate that, despite the negative influence of GFRP added to the timber, they were able to reduce the environmental impacts by reducing the amount of used timbers.

The LCA of FRP bars used as reinforcements in beams was compared to steel bar reinforcements, and it was investigated by different scholars. The results for some of these studies are summarized in Table 8 as a percentage of improvement for FRP compared to steel. Most of the studies showed an improvement when FRP was used as a replacement for steel, but negative effects were found in [34] when the CFRP-SWSSC beam achieved a worse environmental performance than the SRC beam in four categories out of eight, which were ozone depletion (SOD), freshwater eutrophication (FE), freshwater eco-toxicity (FRET) and fossil depletion (FD), and the GFRP-SWSSC beam performed worse than the SRC beam in two categories: freshwater eutrophication (FE) and fossil depletion (FD).

Table 8. LCA of different studies showing the improvement made by using FRP bars instead of steel bars as a percentage (%).

Environmental Impact Category	[35]	[34]	[116]	[35]	[36]	[34]	[35]
	CFRP Beam	**GFRP-SWSSC Beam**	**BFRP Beam**	**BFRP Beam**	**BFRP Beam**	**CFRP-SWSSC Beam**	**GFRP Beam**
Climate change	-	26	38	-	-	29	-
Global Warming Potential	39	-	-	40	7	-	43
Energy consumption	32	-	-	50	-	-	47
Ozone depletion	-	1	40	-	4	−83	-
Terrestrial acidification	-	15	43	-	9	37	-
Freshwater eutrophication	-	−97	85	-	13	−107	-
Marine eutrophication	-	-	42	-	17	-	-
Human toxicity	-	2	78	-	-	1	-
Photochemical oxidant formation	-	-	47	-	-	-	-
Particulate matter formation	-	20	57	-	10	40	-
Terrestrial eco-toxicity	-	-	52	-	12		-
Freshwater eco-toxicity	-	4	84	-	15	−8	-
Marine eco-toxicity	-	-	84	-	18	-	-
Ionizing radiation	-	-	26	-	4	-	-
Agricultural land occupation	-	-	48	-	-	-	-
Urban land occupation	-	-	44	-	-	-	-
Natural land transformation	-	-	36	-	-	-	-
Water depletion	-	-	24	-	6	-	-
Metal depletion	-	-	96	-	-	-	-
Fossil depletion	-	−3	48	-	5	−23	-
Ozone formation: human health	-	-	-	-	7	-	-
Ozone formation: terrestrial ecosystems	-	-	-	-	7	-	-
Human carcinogenic toxicity	-	-	-	-	21	-	-
Human non-carcinogenic toxicity	-	-	-	-	14	-	-
Land use	-	-	-	-	10	-	-
Mineral resource scarcity	-	-	-	-	20	-	-

4.2. Life Cycle Assessment of FRP Used in Bridges

Structural projects such as bridges affect natural environments negatively in variable ways during their total life cycle. In order to reduce environmental impacts and to improve sustainability resulting from bridge construction, some measures should be taken into account, such as reducing energy consumption, emissions to the environment, waste generation and the usage of raw materials. A study performed by the authors of [123] examined the sustainability of a bridge with a GFRP deck solution compared to an existing traditional composite (concrete/steel) bridge with a deteriorated concrete deck by taking into consideration its life cycle, construction process and maintenance. The study shows that the bridge with a GFRP deck causes a reduction of around 20% in carbon emissions compared to the concrete deck bridge. The authors of [124] investigated the environmental performance of CFRP-reinforced concrete, reinforced concrete and mild steel bridges, and it was concluded that the lowest global warming potential (GWP) and abiotic depletion of fossil (ADPF) resources are associated with the CFRP-reinforced bridge. In addition, the acidification potential (AP) of the CFRP-reinforced concrete bridge is higher than that of the other bridges. LCA was conducted in a study by the authors of [125], where a comparison was made between an FRP footbridge under a severe environment and a conventional concrete bridge. It was reported from the study that the FRP footbridge reduces the total amount of carbon dioxide emissions compared to the conventional PC bridge due to the light weight of the FRP footbridge. The environmental implications of two designs alternatives for a bridge were studied by the authors [126], and an LCA study was conducted to compare an FRP (GFRP/CFRP)-reinforced concrete (RC)/pre-stressed concrete (PC) bridge to a traditional carbon steel (CS)-reinforced concrete/pre-stressed concrete bridge, and the results show that the environmental impact of the FRP-RC/PC design is smaller in four out of five categories, namely acidification (AC), global warming (GWP), eutrophication (EU) and photochemical oxidant creation (POC), compared to the CS-RC/PC design due to its shorter service life. A life cycle assessment was conducted by the authors of [127] for a traditional steel–concrete bridge design, compared to another steel bridge with an FRP deck. The study shows that the steel bridge with the FRP deck has a smaller environmental impact than the traditional concrete-reinforced bridge, where FRP composites in the FPP deck steel bridge contribute less to ozone depletion (OD), fossil depletion (FD), global warming (GWP) and terrestrial acidification (TA), even though freshwater eutrophication (FE) is less in the steel–concrete bridge. The authors of [128] analyzed the LCA of a highway bridge with different maintenance strengthening strategies, where bonding steel plates and bonding CFRP plates were used. The obtained results show that strengthening the bridge with bonding CFRP plates is a better choice than steel plates from an environmental protection perspective, given that the acidification potential (AP) and eutrophication potential (EP) are lower when CFRP plates are used compared to steel plates, and it should be noticed that the biggest contribution to global warming potential comes from the detouring stage, accounting for around 50% of the whole life cycle. An LCA analysis framework was used by the authors of [129] to analyze the environmental impacts of a GFRP footbridge compared to a standard steel footbridge. It was concluded from the paper that the FRP bridge presents potentially worse environmental impacts resulting from the production of FRP compared to the steel bridge. The life cycle environmental performance of an FRP deck in a UK highway bridge was compared to a conventional concrete deck by the authors of [130]. The results show that the accumulation of carbon emissions during the service life of 120 years for the FRP deck resulted in fewer carbon emissions at the initial constriction stage, and the pre-stressed concrete deck resulted in approximately 13% fewer carbon emissions than the FRP deck over its entire life service, which makes is more desirable over its entire design life. The author of [131] investigated the environmental advantages of using GFRP composite material compared to traditional materials such as structural steel, stainless steel, aluminum and concrete for a two-span pedestrian bridge in terms of energy consumption. The results indicate that the GFRP bridge requires less than half of the energy input compared to bridges made of other traditional materials. Table 9 summarizes the applications and the environmental impacts of different FRPs used in bridges.

Table 9. Environmental impact of FRPs used in bridges.

Reference	Application	Environmental Impact after Using FRP
[123]	Bridge with a GFRP deck solution compared to (concrete/steel) bridge with a deteriorated concrete deck	Reduction of around 20% in carbon emissions.
[124]	CFRP-reinforced concrete, reinforced concrete and mild steel bridge	Lower GWP and ADPF, and AP is higher.
[125]	FRP footbridge under severe environment compared to conventional concrete bridge	Reduces the total amount of carbon dioxide emissions.
[126]	FRP(GFRP/CFRP)-RC/PC bridge compared to CS-RC/PC bridge	The environmental impact is less in four out of five categories, namely AC, GWP, EU, and POC.
[127]	Steel–concrete bridge compared to steel bridge with FRP deck	Reduces the environmental impact (lower OD, FD, GWP and TA) but has higher FE.
[128]	Bonding CFRP plates compared to bonding steel plates	- Lower environmental impact (lower AP and EP). - Detouring stage accounts for around 50% of the whole life cycle during the maintenance stage.
[129]	GFRP footbridge compared to a standard steel footbridge	Presents potentially worse environmental impacts.
[130]	FRP deck compared to a conventional concrete deck	- FRP deck resulted in fewer carbon emissions at the initial constriction stage. - FRP deck option resulted in approximately 13% higher emissions than the concrete deck over the entire design life.
[131]	GFRP compared to traditional materials such as structural steel, stainless steel, aluminum and concrete for a bridge	- GFRP bridge requires less than half of the energy input compared to bridges made of other traditional materials.

4.3. Life Cycle Assessment of FRP Waste Management

Fiber-reinforced polymer composites have been used progressively over the past few years in different applications of civil engineering. Despite the advantages accompanied by the use of FRP, their growing use increases the amount of FRP waste, which raises environmental and economic concerns regarding the need to recycle FRP waste. The main end-of-life pathways for FRP waste are as follows: (1) Landfill: underground storage for waste when no recycling technique is available; (2) Incineration: a thermal technique with partial energy recovery from heat generated by waste combustion; (3) Co-incineration: allows material recovery in addition to energy recovery; (4) Mechanical Recycling: a process to separate fibers from the matrix by a grinding technique. Two fractions result from the process, which are: one that is coarse and rich with a matrix and fibrous, and another part that is rich in fiber; (5) Pyrolysis: a thermal technique that decomposes the matrix at approximately 400–600 °C to recover fibers, (6) Fluidized Bed: the hot air flow fluidizes the sand at 450–550 °C, which volatilizes the matrix and releases the fibers [132–134]. The main end-of-life pathways are summarized in Figure 12.

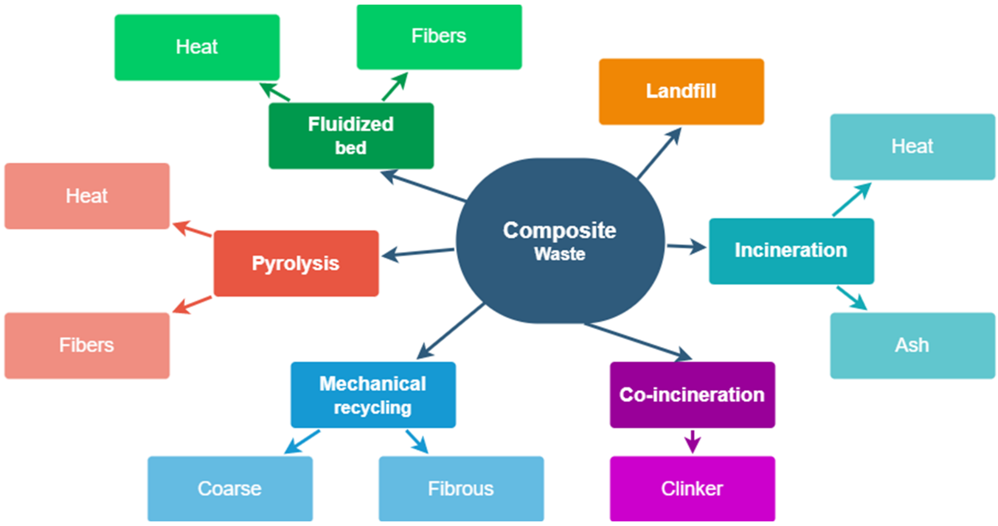


Figure 12. End-of-life pathways for FRP composites.

An LCA was conducted by the authors of [133] to evaluate and compare the environmental impacts of different FRP waste pathways. The Mechanical Recycling, Pyrolysis and Fluidized bed techniques were compared to the Landfill, Incineration and Co-incineration techniques for CFRP and GFRP. The results show that the Pyrolysis technique is the best recycling option for CFRP, and Co-incineration is considered to be more promising for GFRP from an environmental perspective. Another study by the authors of [135] evaluated different waste disposal options for GFRP and CFRP wastes through LCA, targeting the thermal recycling path to reproduce and recycle CFRP and GFRP into recycled composites. Additionally, waste disposal options were compared, including the Landfill technique, Incineration with energy recovery and feedstock in cement kiln production. The LCA results indicate that recycling CFRP wastes using a thermal recycling path results in smaller environmental impacts, with good potential to replace virgin CFRP. Furthermore, using GFRP wastes as a feedstock in cement kiln production showed smaller environmental impacts compared to those thermally recycled. The LCA model was developed by the authors of [136] to quantify the environmental impacts of mechanical recycling for CFRP, and they compared it to the Landfill and Incineration disposal routes. It was concluded that the Landfilling route is not favorable from an environmental perspective and that Incineration experienced the smallest energy demand for processing CFRP waste; however, it has the highest GHG emissions compared to other methods. Furthermore, mechanical recycling was found to be the only path that can reduce GHG emissions and energy consumption, but this method is only applicable if the recycled carbon fibers displace the virgin carbon fiber on a large scale to increase revenue. Furthermore, three end-of-life treatment methods, namely Landfilling, Incineration and Pyrolysis recycling for CFRP waste, were studied by the authors of [137] using the LCA method to evaluate their environmental benefits. The results indicate that the recycling option appears to be the best environmental option compared to Landfilling and Incineration options when virgin carbon fiber (VCF) is replaced with recycled carbon fiber (RCF), but it is not preferable when virgin glass fiber (VGF) is replaced with RCF.

5. Conclusions and Discussion

The reported results from the literature were consistent with one another, since utilizing FRP composites in structures improves stiffness and strength and reduces the environmental impacts resulting from traditional materials.

- Carbon, glass, basalt and aramid are strengthening fibers that are combined with a matrix to produce FRP composite systems. Moreover, some new materials have huge potential to be used as strengthening materials. External FRP strengthening provides a number of benefits over other materials, such as having the ability to resist corrosion, a lower maintenance cost and reduced construction time.

- When FRP is used as a strengthening material to any structural element, such as beams, its influence in terms of the reaction with the ecosystem, long-term service and properties should be considered. However, over the years, a great reputation has been obtained by FRP composites, which has made international construction and design agencies offer construction and design codes.
- FRP composite usage in the industry is significantly advancing over time; thus, many techniques and methods are still under investigation, such as investigations into the effectiveness of FRP strengthening under fatigue loading.
- The authors have deduced some points: The use of anchors enhances shear capacity by 30–50%. Using U-jackets as an anchor system can change the failure mode from FRP debonding to FRP rupturing. MF-EBR increases the flexural capacity of the beams by almost double the value of the EBR-strengthened beam. The ductility of MF-EBR is double the value of the NSM beams.
- It was found that, as FRP thickness increases, two different things result, which are: load-carrying capacity increases when the FRP rupture is the controlling failure mode, and the flexural stiffness within the elastic range increases.
- Replacing conventional steel reinforcement bars with FRP bars as partial reinforcement or total reinforcement improves the stiffness and capacity of the structural members. However, due to its brittle properties, large crack widths are experienced for structural members with high reinforcement ratios of FRP bars. Therefore, a hybrid system may be explored to provide ductility to the structure and inhibit corrosion problems.
- The environmental impact of BFRP rebars is smaller than that of traditional steel, in which a reduction in the emissions emitted to the environment is expected. BFRP rebars are a promising option for RC members in contrast to steel rebars as a result of their light weight and high strength.
- Adopting the utilization of sea-sand and seawater in concrete leads to a reduction in the environmental impact in comparison to the use of traditional concrete with freshwater and river sand. GFRP-SWSSC beams and CFRP-SWSSC beams have a better environmental impact compared to steel-reinforced beams.
- The use of GFRP, CFRP and BFRP in structures instead of steel may lead to reduced energy consumption and CO_2 emissions, thus reducing their environmental impacts over their life cycles.
- Many researchers have focused on evaluating the LCA of FRPs in structural members. Nevertheless, some aspects still need to be addressed to explain the environmental impact of FRP and to enhance the quality of results of the life cycle assessment.
- The interaction between economic impacts and environmental impacts of distinct FRPs should be explored, evaluated and compared to conventional materials such as steel to encourage decision makers and buyers to increase their use of FRP to have a better substitute in the future for other reinforcing materials in structural elements.
- FRPs were mainly used in literature as a partial reinforcement in structural members to replace steel; therefore, it was suggested by the authors to apply comprehensive LCA studies for different FRPs, where they are utilized as a full-scale reinforcement instead of traditional steel for structural members.
- Many researchers have evaluated the life cycle assessment of different FRPs by applying cradle-to-gate boundaries; therefore, extra LCA studies considering the full life cycle of the FRP are required, beginning with obtaining raw materials and ending with the final disposal of the FRP (cradle to grave).
- Additional LCA studies have been suggested by the authors to be applied to evaluate the environmental impacts of utilizing FRPs as a non-corrosive reinforcement in concrete structures when seawater is replaced by freshwater in concrete.
- Enhancing and developing the design codes for FRPs used in RC beams and bridges can encourage the progressive use of FRPs in construction.

- FRP materials cause higher carbon emissions compared to conventional materials during the production stage, but high carbon emissions are compensated during maintenance, construction or disposal phases due to the light weight of FRP decks. Therefore, bridges with FRP decks have less energy consumption and carbon emissions compared to bridges with traditional materials.

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