Performance of Fiber Reinforced Polymers in Concrete for Sustainable Construction Industry

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Abstract: The construction industry is widely known for having a significant negative impact on the environment as a result of the massive volumes of raw materials consumed and greenhouse gas emissions. Therefore, during their service life, scientists need to promote and research the environmental effects of employing alternative alternatives like fiber-reinforced polymers (FRP). Due to its longevity, great corrosion resistance, light weight, and high strength, FRPs have become more and more popular in recent years. One of the most crucial techniques for examining the effects of the FRP on the environment is life cycle assessment. The purpose of this work is to provide an overview of fiber-reinforced polymer composites used in concrete structures with an emphasis on their mechanical and environmental characteristics in structures used in civil engineering. The life cycle assessment approach is used to evaluate the environmental effect of fiber-reinforced polymers, their usage as a strengthening mechanism in concrete structural components, and their qualities. According to the literature's published findings, using FRP composites in structural members rather than conventional ones increases their strength and stiffness and lessens their environmental effect.

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

1. Introduction

One of the most important areas in the world that supports the growth of nations and their economies is the building industry. The industry's contribution to the world gross domestic product (GDP) in 2020 was 26% [1]. Nevertheless, despite its many benefits, it was inevitable that the industry would become the focus of worry for many scientists due to its direct impact on the environment, as it consumes 40% of global natural resources annually, 40% of energy, 25% of global waste, 15% of the world's freshwater resources, and 40% of greenhouse gas (GHG) emissions [2-4]. In addition to having a negative impact on the environment, conventional structures deteriorate over time and require expensive maintenance, which highlights the need for finding innovative ways to build new structures with lower maintenance costs, longer lifespans, and greater environmental and weather resistance [5]. Utilising more environmentally friendly building materials, such as fiber-reinforced polymer (FRP) composites, as reinforcement or as a strengthening option for construction, as opposed to conventional materials, is one feasible strategy. The basic building block of FRP composites, also known as advanced polymer composites (APC), is a polymer matrix made of resins like polyester, vinyl-ester, and epoxy reinforced with various grades of basalt, aramid, carbon, or glass fibres [6,7]. In addition, FRP composites have become extremely well-liked in the civil engineering community in recent years because of their beneficial qualities, including their low weight in comparison to conventional steel, nonmagnetic traits, usability, non-corrosiveness, high specific stiffness in comparison to conventional materials, and non-corrosive nature [6–10]. FRP composites still have certain drawbacks, such as their high cost, the rapid loss of strength and stiffness at high temperatures, limited ductility, low shear strength, and the difficulty in bending FRP rebars that are now on the market [11]. FRP composites are fully utilised in new projects, however in other instances, they are just partially utilised in the rehabilitation (retrofitting, strengthening, and repairing) of an existing structure [12,13]. In some instances, FRPs are used to strengthen masonry walls [24], while in other instances, 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]. By combining the fibres with cement and putting it to the soil, chopped fibres are also used to increase the concrete's compressive strength and to stabilise the soil [25]. Carbon-fiber reinforced polymer (CFRP), aramid-fiber reinforced polymer (AFRP), glass-fiber reinforced polymer (GFRP), and basalt-fiber reinforced polymer (BFRP) are the most popular forms of FRP composites used in construction.

The key benefits of CFRP over other forms of FRPs are its high tensile strength and high elastic modulus, which minimise deformations in CFRP reinforced parts. Due to its high tensile strength compared to traditional steel and relatively low cost compared to other forms of FRPs, GFRP is primarily the most often used reinforcing fibre for polymeric matrix composites. However, GFRP has an elasticity modulus that is four to five times lower than conventional steel, which causes more deformations in GFRP reinforced parts [22].

Additionally, FRP's corrosion resistance, durability, lightweight, and economic advantages throughout the lifecycle of construction aid in reducing energy use and greenhouse gas (GHG) emissions, which are produced during the maintenance, transportation, installation, and production processes. Fiber-reinforced polymers (FRPs) are an excellent substitute for conventional construction materials, and rising worries about global warming and the depletion of natural resources have made it necessary to investigate the environmental effects linked to the use of FRPs in structures [7]. The life cycle assessment (LCA) approach is one of the instruments created to define and analyse the environmental consequences of a product across its lifespan stages. The ISO 14040:2006 standard describes LCA as "the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle". LCA examines the whole life cycle of a product, including the gathering of raw materials (cradle), manufacture, usage, recycling, and final disposal (grave). The aim and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation process are the four main components of the LCA framework. Figure 1 describes the LCA flow chart, which includes the input and output flows of materials, energy, and pollutants. To characterise the environmental effects of FRP used in, several life cycle assessment studies have been created.

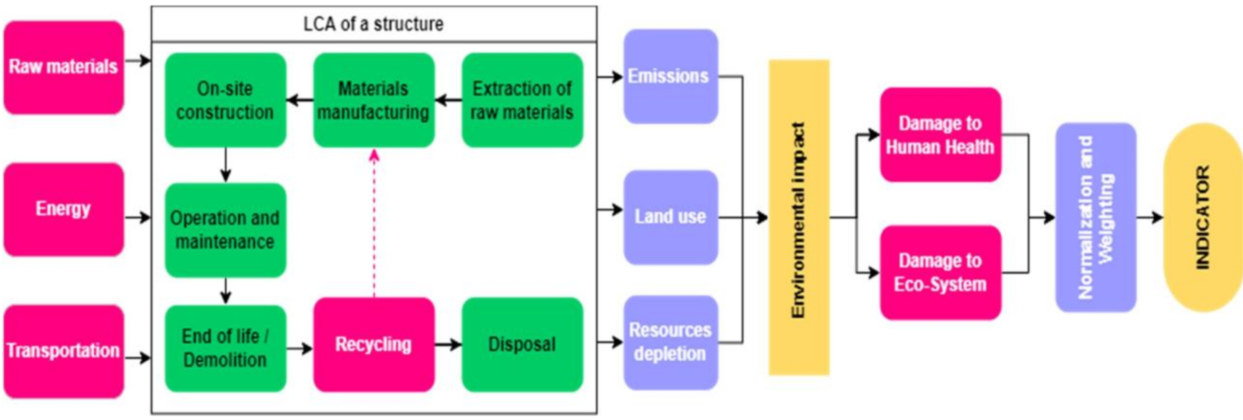

Figure 1. Flow chart of the LCA, including input and output flows of materials, energy and pollutants from a life cycle perspective.

2. Research Methods

Composites made of fiber-reinforced polymers are employed in a variety of industries. FRPs have been utilised in building since semi-load-bearing and infill panels composed of GFRP were first employed in construction in the 1970s. The first FRP bridge built on a public roadway was in Oxfordshire, UK, while the first pedestrian bridge made entirely of FRP was built in Tel Aviv in 1975. The bridge's construction was finished by 2002. The literature of interest was established using the steps below. In step 1, Google Scholar, ResearchGate, Science Direct, and Scopus were used to conduct a thorough search. In published publications, the following keyword combinations were looked up: "life AND cycle AND assessment AND fibre AND reinforced AND polymer" or "fibre AND reinforced AND polymer AND concrete AND structures." Peer-reviewed literature such as journal articles, review papers, and conference proceedings were the only sources that were considered. In rare instances, additional sources including websites and books were also used. Stage 2 of the filtering process included examining keywords, titles, and abstracts. The search rejected any papers that did not specifically discuss the LCA of FRP, the mechanical performance of FRP, or the strengthening of structural components using FRP. Stage 3 involved carefully reading and evaluating the complete articles to decide whether they were appropriate.

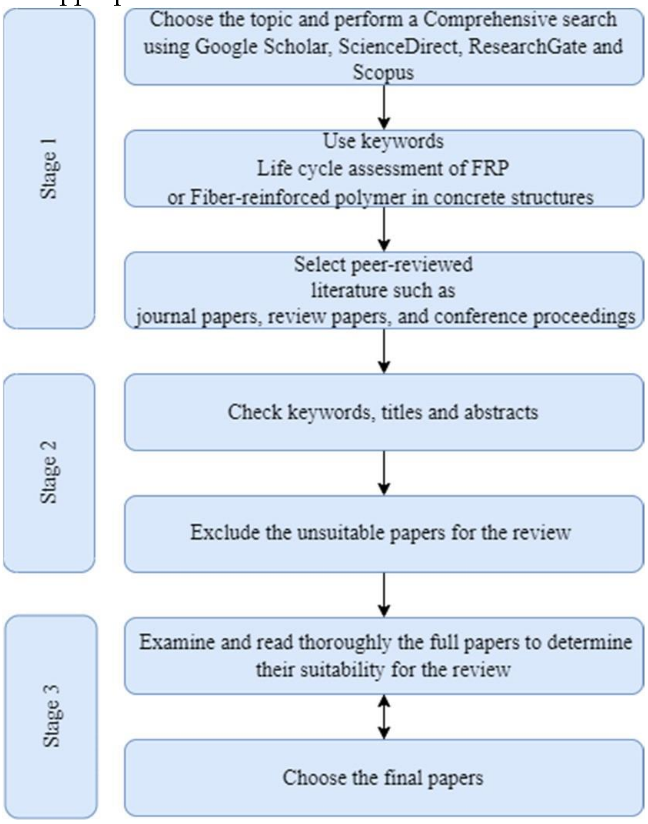

Figure 2. Research methodology.

3. Materials and Mechanical Behavior of FRPs

3.1. Mechanical Behavior of FRP Composites

FRP composites have gained popularity in the construction sector due to its superior usage as reinforcement over steel in a number of areas, including greater mechanical qualities, cost, durability, and corrosion resistance. It has been documented how various FRP composites behave mechanically in both FRP sheets and FRP bars. The four FRP composites that are the subject of this research are carbon (CFRP), glass (GFRP), basalt (BFRP), and armid (AFRP).

3.1.1. CFRP Composites

Carbon fibres are distinguished by their high deformation modulus, which is comparable to that of steel, high fatigue strength, and resistance to water absorption. Carbon fibres typically have diameters between 5 and 10 m, and when made into CFRP bars using the pultrusion method, they offer a very high tensile strength. In Table 1, the mechanical characteristics of CFRP bars are shown. These characteristics include density, tensile strength, deformation modulus, elongation, coefficient of thermal expansion, and Poisson's ratio. Although compared to normal steel, CFRP bars can offer mass reductions of 40–60%, the production cost is 1.5–10 times higher when material and processing expenses are taken into account.

3.1.2. GFRP Composites

Due to its economic efficiency when compared to all other FRP fabrics, GFRP bars are the most often utilised. The mechanical characteristics of GFRP bars are known to have low humidity, poor alkaline resistance, and low long-term strength owing to stress rupture.

3.1.3. BFRP Composites

Over the past 10 years, there has been a lot of study done on the uses of BFRP fibres. Excellent mechanical and durability features may be found in BFRP fibres. They also exhibit remarkable resistance to radiation, high temperatures, corrosion, and UV exposure.

3.1.4. AFRP Composites

Due to its low long-term strength, susceptibility to UV rays, and difficulties in processing and cutting, AFRP composite bars have a restricted application. The superior impact resistance of AFRP fibres contrasts this.

3.1.5. Matrix of FRPs

To create the composite bars and sheets, the fibres are mixed with a matrix made up of resins and other additives. Resins come in two primary categories. Thermoplastic resin, for example, can change in hardness or pliability depending on the temperature. (b) Thermosetting resin: This substance is made by irreversibly hardening a soft viscous fluid using radiation or curing. The most popular resin is thermosetting because, once it has hardened, it is not temperature-sensitive. The physical and mechanical characteristics of three of the most popular thermosetting resins, including polyester, epoxy, and vinyl-ester resins.

3.2. Strengthening of RC Beams Using FRP Composites

In order to strengthen the application of RC structural components, FRP composite sheets are employed. For the shear and flexural strengthening of beams utilising externally bonded FRP materials, a variety of strengthening methods and patterns can be applied.

Strengthening Patterns

For the shear and flexural strengthening of beams utilising externally bonded FRP materials, several strengthening techniques and patterns may be applied, which can be on the plane of the beam cross-section. Both discontinuous and continuous strengthening patterns are possible. Consideration should be given to moisture migration in the event of continuous wrapping. Using the wet layup process, there are three primary options for attaching FRPs to the cross-section of the beam:

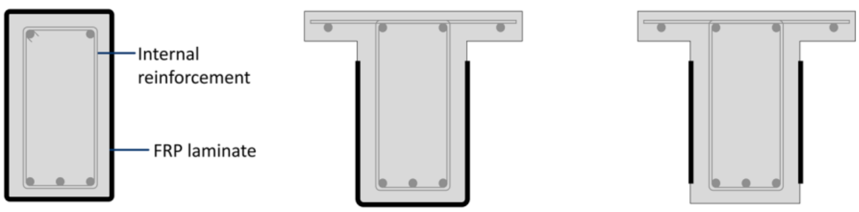

Figure 2. Different FRP wrapping schemes.

- 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

Regarding the installation of FRP anchors, there aren't many rules. The design parameters for shear strengthening beams utilising externally bonded CFRP are specified in ACI 440.2R-08. According to research, the anchorage is influenced by the anchor layout, the anchor hole inclination from the axis perpendicular to the surface, the depth and area of the anchor hole, the radius of the anchor hole chamfer, the amount of CFRP materials in the anchors, the length and angle of the anchor fan, and the anchor reinforcement.

3.4. Failure Modes

In FRP composites, several failure mechanisms can occur. As shown in Figure 5, the three most frequent failure mechanisms are fabric rupture, concrete separation, and FRP material debonding.

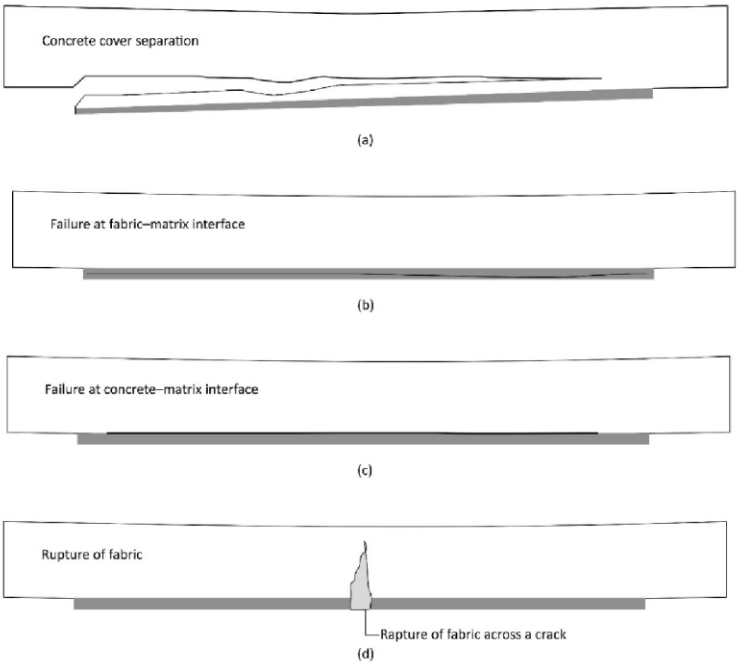

Figure 3. Illustration of failure modes.

3.4.1. Concrete Separation

The top and/or bottom of the beams may encounter longitudinal cracks that develop sequentially to increase the number of shear fractures on the shear span, leading to the collapse of the beams. This is known as concrete separation failure. Later, the concrete's lateral layer splits. Several research have reported on this. The improved bonding properties between the FRP and concrete substrate are what cause this kind of failure.

3.4.2. Debonding of FRP

The debonding failure mode is the most frequent method of failure for the reinforced beams using the FRP system, however there are other types as well. This kind may be identified easily by a transverse fracture that grows towards the unloaded sections from close to the loading site.

3.5. Beam Strengthening in Shear

To increase RC beams' ability to resist applied forces, FRP materials are employed in the shear, flexural, and torsional strengthening and rehabilitation processes. When the shear capacity after flexural strengthening of the beam is more than the flexural capacity, shear strengthening must be done. The placement of the primary fibre direction parallel to the highest principal tensile force, which is typically at an angle of around 45 degrees to the horizontal axis of the member, is an efficient design strategy for shear strengthening. The fibres are preferably joined perpendicular to the axis of the part, however this is more practicable. In the study by Baggio et al. (2014), beams with dimensions of 150 mm broad by 350 mm deep were cast and strengthened using a U-wrap scheme and glass- and carbon-fiber reinforced polymers (GFRP) and carbon-fiber reinforced polymers (CFRP) with and without anchors. The wrapping method was set up as the authors investigated the impacts of both full-depth and partial-depth FRP U-wrap. According to this study, using full-depth GFRP without anchoring resulted in a 50% increase in shear capacity over the control beam. However, the shear capacity of the beams reinforced with partial-depth GFRP increased by 52% and 36%, respectively, for the beams with and without anchors.

Investigations into shear strengthening with CFRP and a U-wrap system were conducted. The parameter that needed to be altered was the distance between the fibres. The casted beams had dimensions of 2000 mm in length, 300 mm in depth, and 120 mm in width. Sikadur-41 and Sikadur-31 CF epoxy were used. Figure 4 depicts the wrapping scheme's setup. Figure 8 provides a summary of the failure modes that were encountered. The U-wraps were only 22% engaged when the fibre failed due to debonding from the concrete beam, it should be emphasised.

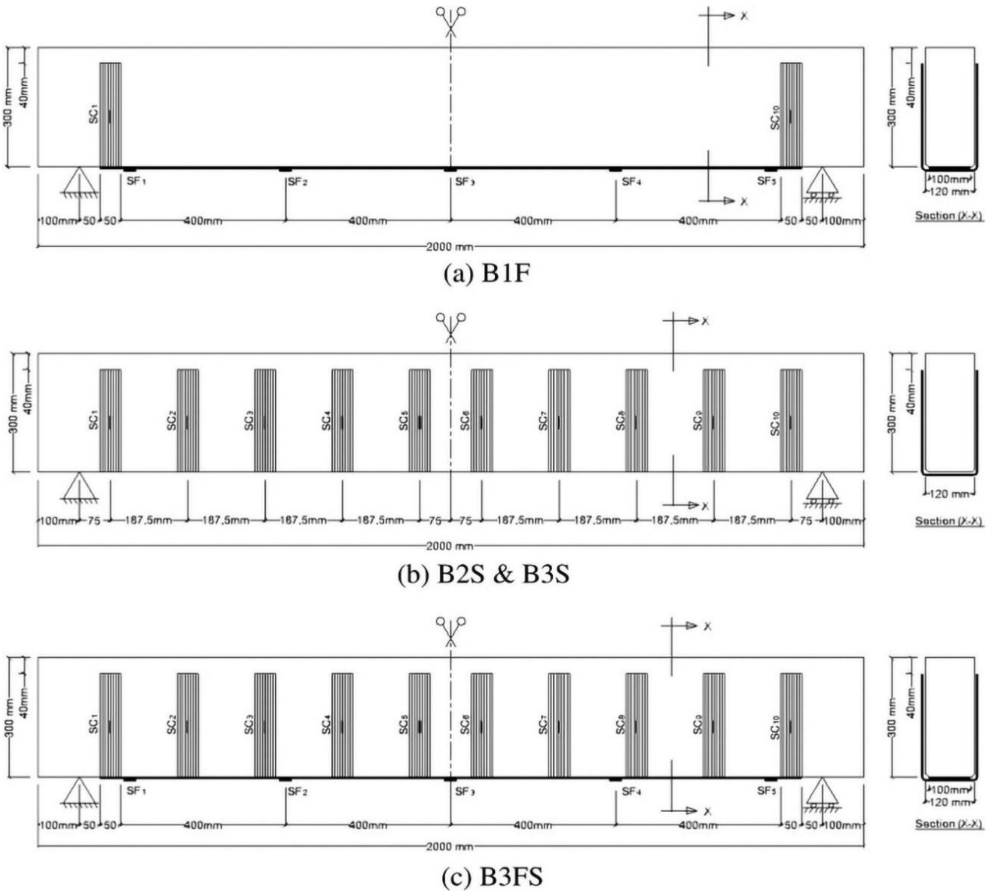

Figure 4. Wrapping scheme for shear strengthening [59].

3.7. Strengthening of RC Columns Using FRP

3.7.1. Wrapped Concrete Columns with FRP

Concrete columns (CC) are susceptible to failure if the lateral strain exceeds its limit, the concrete cover starts to fracture, and the steel reinforcement buckles. Therefore, delaying the CC's lateral strain from reaching its limit can improve the CC's performance. This may be done by applying lateral pressure to the diameter of the column while wrapping the CC in FRP around its circumference. Maintaining fibre orientation in a transverse direction to the column is essential to confinement theory. This theory's justification is the lateral expansion brought on by the axial load. Due to the tensile strains created by this lateral expansion in the confinement material, the CC is under confining pressure.

3.7.2. Advantages of Wrapped Concrete Columns with FRP

Because the confinement of concrete columns with FRP materials enhances the capacity of the member and its ultimate strain, it reduces the likelihood of failure due to the unexpected load resulting from an earthquake or other load type. A durable formwork and non-corrosive reinforcement that shields the CC from hostile surroundings are other functions of the FRP-confined material. In addition, Qasrawi et al. noted that employing FRP-confined CCs under blast loading results in less localised damage than using traditional RCCs, which helps protect people and property from unintentional or deliberate explosions.

3.7.3. Different Parameters Affecting the Confinement of RC Columns

According to various factors, including cross-section shape, slenderness ratio, concrete strength, manufacturing method, fibre properties, fibre orientation, and FRP thickness, confining concrete columns with FRP enhances the member's strain and axial strength capacities to a certain extent.

3.7.4. Slenderness Ratio

It has been investigated in the past how slenderness affects the axial performance of high strength and standard strength concrete encased in circular FRP tubes. It was determined that when the slenderness ratio increased, the degree of strain and strength increases dropped. Additionally, it was shown that circular reinforced concrete columns covered in FRP material are less significant in slim columns than in short columns.

3.7.5. The Shape of Concrete Columns

According to Fam et al., Hong and Kim, Pessiki et al., and Mirmiran et al., FRP confinement has a less significant impact on the behaviour of non-circular columns than it does on circular cross-sections. Their findings have shown that, due to the noncircular FRP tubes' tendency to flex outwardly on their flat sides, confining noncircular columns is not as successful as confining circular columns. Following testing on spherical and square FRP specimens filled with geopolymer concrete while using axial compression, Ozbakkaloglu and Xie came to the same result. Therefore, two approaches were used by researchers to enhance rectangular and square concrete confinement columns, changing the cross-section into circular and elliptical sections, respectively, in order to solve this issue. The first method included enclosing the original concrete column with prefabricated FRP shells, which were then filled with concrete to create a circular form.FRP shells were fixed as sheets or strips using a wet lay-up procedure.

In order to alter the square CC cross-section, Beddiar et al. adapted the initial method by collecting three sheets of GFRP formed of twill weave glass that had structural bending. They then filled the space with shrinkage-reimbursing cement mortar, as illustrated in Figure 5. According to test data, cross-section changes can increase the ductility and strength of non-circular concrete columns.

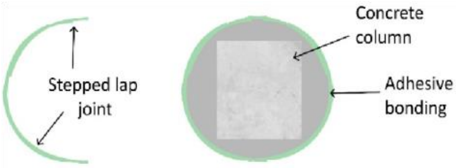

Figure 5. Modifying square concrete columns by using GFRP shell stepped lap joint.

Bhowmik et al. 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 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, 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

On top of the research done by Kim et al. and Hong and Kim, more research has been done. These further investigations were carried out by Vincent and Ozbakkaloglu, who looked at the impact of fibre orientation on the axial behaviour of constrained concrete samples in the FRP tube. They created multiple tube types utilising the filament winding process, employing CFRP orientated at varied angles with the axial direction as the reference. The study found that the orientation of the fibre has an influence on the axial performance of the confined samples, and that this effect is greatest when the FRPs are orientated in the hoop direction.

3.7.8. Stress–Strain Behavior of FRP

Two basic categories may be used to categorise the strain. The first is the effective ultimate strain fe, while the second is the ultimate strain fu. Through performing tests and calculating the strain till jacket rupture, it has been discovered that the effective ultimate strain is significantly lower than the ultimate strain. The ratio between the two strains, which is connected to one another, is commonly referred to as the strain efficiency factor, or ks = f e/fu. Two alternative tests, flat coupon tensile testing and split desk test specimen, can be used to characterise the tensile behaviour of FRP in order to determine its properties. The circumferential bending of the FRP ring at the gap between the two half discs and the discontinuities of the geometry at the ends of the FRP are the reasons why the split desk test exhibits lower values of ultimate strain than split desk test specimens. The statistics that are supplied by the manufacturers are frequently derived from flat coupon testing, which are commonly utilised. The tri-axial state of jacket stress, execution quality, reinforcement curved shape, local stress concentrations at the concrete core due to inhomogeneous deformation, cracking, and size effects when using multiple layers have been listed as potential causes of the discrepancy between effective ultimate strain and ultimate strain.

3.7.9. Axial Loads on FRP Columns

Considerations for columns should include axial loads and bending moments. The load that passes from slabs and beams to columns is typically known as the axial load, and it is typically a compression force. The axial load was the main emphasis of Irshidat, Al-Saleh, and Al-Shoubaki's investigation into the adequate strengthening of carbon fiber/epoxy-composite-wrapped RC. For testing, a total of 14 rectangular crosssection RC columns were built. The experiment's findings revealed that using epoxy resin modified with CNT increased the wrapped columns' toughness and axial load bearing capability by 19% and 12%, respectively. Additionally, as demonstrated in Table 4, the CNT-enriched sizing agent (SCNTE) increased the axial carrying capacity of columns by 15% compared to plain epoxy (NE) specimens. It demonstrated a solid link between the fibre and concrete, which justified the columns' rising strength. One of the worst settings for RC constructions has been identified as high temperatures. High temperature exposure to RC columns frequently has negative consequences such concrete retrogradation, strength loss, and spalling. Irshidat and Al-Saleh looked at how carbon nanotubes (CNTs) affected the axial load capacity of heat-damaged RC columns that had been repaired using composites made of carbon fibre reinforced polymer (CFRP). For testing, columns were cased and given a 28-day curing period. After that, the samples were heated for two hours in an electrical oven to temperatures between 500 and 600 degrees Celsius. The damaged columns were then repaired using the composites modified with CNT.

It is thought to be more cost-effective to improve a model to predict the hollow FRP composite column's axial strength with buckling effects. Barbero and Tomblin looked at the regional and global pultruded I-section of FRP broad flange buckling. Based on their experimental findings, they presented design equations that, in the view of academics, have been working well to predict the intermediate length critical loads of FRP-I section columns. By utilising a model of strain energy density that made use of the region under the column axial stress-strain curve, GangaRao and Blandford used several techniques to forecast FRP column axial strength. The major goal of their research was to examine the global buckling and local impacts on the strength of the pultruded GFRP compression component.

4. Environmental Performance of FRP

It has recently become crucial to look into the environmental effects of new products, especially those that have a long service lifetime compared to others, like FRPs, green concrete, and steel, as a result of growing environmental issues like climate change, global warming, and the depletion of natural resources. Due to their longevity and resistance to corrosion, fiber-reinforced polymers outperform conventional materials in terms of sustainability and environmental friendliness. The authors of [36] carried out an LCA analysis in which steel-reinforced BFRP bars and non-corrosive bars were compared. In comparison to steel, galvanised steel, GFRP, and stainless steel, it was discovered that BFRP rebars had the least negative effects on the environment throughout the eighteen criteria categories under consideration. In comparison to steel, galvanised steel, GFRP rebars, and stainless steel, BFRP rebars' global warming potential was rated at 74%, 49%, 44%, and 88% lower, respectively. The environmental effect of GFRP was evaluated in a different research by the authors of by contrasting it with conventional steel rebar at the production stage. According to reports, GFRP has generally more negative environmental effects than steel in most cases, especially when it comes to climate change, inorganic respiratory toxins, and fossil fuels.

4.1. Life Cycle Assessment of FRP Used in Beams

Modern structural components ought to reduce their environmental effect while also performing better functionally. Fiber-reinforced polymers have emerged as potential materials that may be employed in a variety of civil engineering applications in place of conventional materials like steel in recent years due to their favourable endurance properties. Concrete and steel are the most commonly used materials worldwide, second only to drinking water however, their use results in additional CO2 emissions into the atmosphere, a dramatic depletion of resources, and climate change as a result of global warming. Several academics have employed various techniques to reduce the environmental burden brought on by conventional materials to improve, The authors of conducted an LCA assessment for various concrete beams to examine the environmental effects of using BFRP bars as reinforcement in place of steel bars. The calculated results show that the eighteen environmental indicators considered in the study performed much better when BFRP bars were used as reinforcement in concrete beams as opposed to steel bars. By decreasing emissions that contribute to climate change, ozone depletion, human toxicity, and freshwater eutrophication by 38%, 40%, 78%, and 85%, respectively, in comparison to conventional steel, BFRP is a greener alternative for concrete than steel.

Different researchers evaluated the LCA of FRP bars used as reinforcement in beams to that of steel bar reinforcements. Table 8 presents the findings for several of these investigations as a percentage improvement for FRP over steel. Most studies indicated an improvement when FRP was used to replace steel, but adverse effects were discovered in [34], where the CFRP-SWSSC beam performed worse environmentally than the SRC beam in four out of eight categories, including ozone depletion (SOD), freshwater eutrophication (FE), freshwater eco-toxicity (FRET), and fossil depletion (FD), and the GFRP-SWSSC beam performed worse environmentally than the SRC beam in two categories, including freshwater.

4.2. Life Cycle Assessment of FRP Used in Bridges

Throughout its entire life cycle, structural structures like bridges have a harmful impact on the environment in a variety of ways. Some measures, such as minimising energy consumption, emissions to the environment, trash generation, and the use of raw materials, should be taken into consideration in order to lessen the negative environmental effects and promote sustainability arising from bridge building. The life cycle, building method, and maintenance of each bridge were considered in research by the authors of to evaluate the sustainability of a bridge with a GFRP deck solution to an existing traditional composite (concrete/steel) bridge with a degraded concrete deck. According to the study, the bridge with a GFRP deck reduces carbon emissions by around 20% when compared to the bridge with a concrete deck. The CFRP-reinforced bridge has the lowest potential for global warming (GWP) and abiotic depletion of fossil fuels (ADPF), according to the authors of, who studied the environmental performance of CFRP-reinforced concrete, reinforced concrete, and mild steel bridges. Additionally, the CFRP-reinforced concrete bridge has a larger acidification potential (AP) than the other bridges. A comparison between a standard concrete bridge and a FRP footbridge in a harsh environment was undertaken using LCA in research by the authors of According to the study, the FRP footbridge's lighter weight than the traditional PC bridge results in a reduction in the overall quantity of carbon dioxide emissions. The LCA of a highway bridge with various maintenance strengthening measures, including the usage of bonded CFRP and steel plates, was examined by the authors. Given that the acidification potential (AP) and eutrophication potential (EP) are lower when CFRP plates are used compared to steel plates, the obtained results demonstrate that strengthening the bridge with bonding CFRP plates is a better choice from an environmental protection perspective than steel plates. It should be noted, however, that the biggest contribution to global warming potential comes from the detouring stage, accounting for about 50% of the entire life cycle. The authors of evaluated the environmental effects of a GFRP footbridge to a traditional steel footbridge using an LCA study methodology. According to the findings, the pre-stressed concrete deck produced roughly 13% fewer carbon emissions than the FRP deck over the course of its 120-year service life, making it more desirable over the course of its entire design life. The FRP deck produced less carbon emissions at the initial stage of construction. In the author looked into the environmental benefits of employing GFRP composite material over more conventional materials for a two-span pedestrian bridge, such as structural steel, stainless steel, aluminium, and concrete. The findings show that when compared to bridges built of other conventional materials, the GFRP bridge uses less than half the energy.

Over the past few years, fiber-reinforced polymer composites have been increasingly utilised in a variety of civil engineering applications. The rising volume of FRP trash, notwithstanding the benefits associated with its usage, creates worries for the environment and the economy on the necessity of recycling FRP waste. The following are the primary end-of-life paths for FRP waste: When recycling methods are unavailable, there are four options for waste disposal: (1) landfills; (2) incinerators; (3) co-incinerators; and (4) mechanical recycling, which uses a grinding technique to separate fibres from the matrix and recovers some of the energy produced during waste combustion.

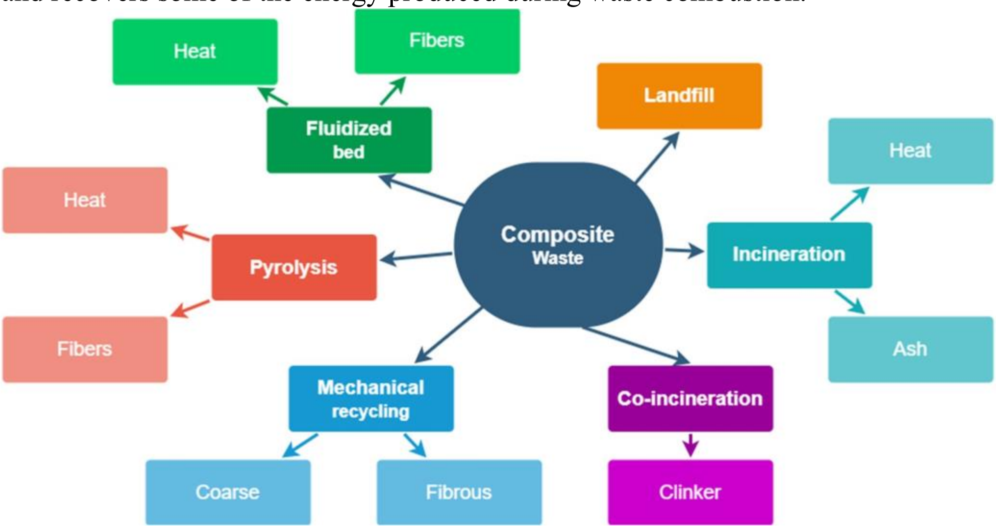

Figure 12. End-of-life pathways for FRP composites.

5. Conclusions and Discussion

Since using FRP composites in constructions enhances stiffness and strength and lowers the environmental consequences brought on by using traditional materials, the reported results from the literature were consistent with one another.

- FRP composite systems are created by mixing strong fibres such carbon, glass, basalt, and aramid with a matrix. Additionally, the possibility for using novel materials as strengthening materials is enormous. In comparison to other materials, external FRP strengthening offers a variety of advantages, including the capacity to withstand corrosion, cheaper maintenance costs, and quicker construction.
- FRP's effects on the environment, long-term service, and characteristics should be taken into account when it is employed as a reinforcing material for any structural element, such as beams. However, FRP composites have developed a strong reputation over time, leading international building and design agencies to issue construction and design codes.
- As the use of FRP composites grows throughout time, various approaches and methodologies are currently being researched, including studies into how well FRP strengthening performs when subjected to fatigue loading.
- The writers have concluded the following: By 30 to 50%, the application of anchors increases shear capacity. The failure mechanism of FRP may be changed from FRP debonding to FRP rupturing by using U-jackets as an anchor system. The flexural capacity of the beams is nearly doubled by MF-EBR compared to the value of the EBR-strengthened beam. The ductility of MF-EBR beams is two times more than that of NSM beams.
- It was discovered that, where the FRP rupture is the governing failure mode, both the load-carrying capacity and the flexural stiffness within the elastic range increase as FRP thickness rises.
- A lot of studies have looked at the LCA of FRPs in structural members. To clarify the environmental effect of FRP and improve the calibre of the life cycle assessment results, various issues must still be solved.
- To persuade decision-makers and buyers to increase their use of FRP and have a better substitute in the future for other reinforcing materials in structural elements, the interaction between economic impacts and environmental impacts of various FRPs should be investigated, evaluated, and compared to conventional materials such as steel.
- Since steel was mostly replaced by FRPs in literature as a partial reinforcement in structural members, the authors recommended doing thorough LCA evaluations for various FRPs in applications where they are employed.
- Numerous researchers have assessed the life cycle assessment of various FRPs using cradle-to-gate boundaries; consequently, additional LCA studies taking into account the entire life cycle of the FRP, starting with the acquisition of raw materials and ending with the final disposal of the FRP (cradle to grave), are necessary.
- In order to assess the environmental effects of using FRPs as a non-corrosive reinforcement in concrete structures when saltwater is swapped out for freshwater in concrete, more LCA studies have been recommended by the authors.
- FRPs may be increasingly employed in construction by improving and enhancing the design codes for FRPs used in RC beams and bridges.

References

1. World Bank Industry (Including Construction), Value Added (% of GDP). Available online: https://data.worldbank.org/ indicator/NV.IND.TOTL.ZS (accessed on 18 May 2022).
2. Ding, G.K.C. Life Cycle Assessment (LCA) of Sustainable Building Materials: An Overview. In *Eco-Efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labelling and Case Studies*; Elsevier Inc.: Amsterdam, The Netherlands, 2013; pp. 38–62. ISBN 9780857097675.
3. Ramesh, T.; Prakash, R.; Shukla, K.K. Life Cycle Energy Analysis of Buildings: An Overview. *Energy Build.* **2010**, *42*, 1592–1600. [CrossRef]
4. Mokhlesian, S.; Holmén, M. Business Model Changes and Green Construction Processes. *Constr. Manag. Econ.* **2012**, *30*, 761–775. [CrossRef]
5. El-Tahan, M.; Galal, K.; Hoa, V.S. New Thermoplastic CFRP Bendable Rebars for Reinforcing Structural Concrete Elements. *Compos. Part B Eng.* **2013**, *45*, 1207–1215. [CrossRef]

6. Lee, L.S.; Jain, R. The Role of FRP Composites in a Sustainable World. *Clean Technol. Environ. Policy* **2009**, *11*, 247–249. [CrossRef]
7. Sbahieh, S.; Tahir, F.; Al-Ghamdi, S.G. Environmental and Mechanical Performance of Different Fiber Reinforced Polymers in Beams. *Mater. Today Proc.* **2022**, *62*, 3548–3552. [CrossRef]
8. Brigante, D. *New Composite Materials*; Springer International Publishing Switzerland: Napoli, Italy, 2014; ISBN 978-3-319-01636-8.
9. Mugahed Amran, Y.H.; Alyousef, R.; Rashid, R.S.M.; Alabduljabbar, H.; Hung, C.-C. Properties and Applications of FRP in Strengthening RC Structures: A Review. *Structures* **2018**, *16*, 208–238. [CrossRef]
10. Teng, J.G.; Chen, J.F.; Smith, S.T.; Lam, L. Behaviour and Strength of FRP-Strengthened RC Structures: A State-of-the-Art Review. *Proc. Inst. Civ. Eng.-Struct. Build.* **2003**, *156*, 51–62. [CrossRef]
11. Rami Hamad, J.A.; Megat Johari, M.A.; Haddad, R.H. Mechanical Properties and Bond Characteristics of Different Fiber Reinforced Polymer Rebars at Elevated Temperatures. *Constr. Build. Mater.* **2017**, *142*, 521–535. [CrossRef]
12. Van Den Einde, L.; Zhao, L.; Seible, F. Use of FRP Composites in Civil Structural Applications. *Constr. Build. Mater.* **2003**, *17*, 389–403. [CrossRef]
13. Zaman, A.; Gutub, S.A.; Wafa, M.A. A Review on FRP Composites Applications and Durability Concerns in the Construction Sector. *J. Reinf. Plast. Compos.* **2013**, *32*, 1966–1988. [CrossRef]
14. Thériault, M.; Benmokrane, B. Effects of FRP Reinforcement Ratio and Concrete Strength on Flexural Behavior of Concrete Beams.
J. Compos. Constr. **1998**, *2*, 7–16. [CrossRef]
15. Hassan, T.; Rizkalla, S.; Abdelrahman, A.; Tadros, G. Design Recommendations for Bridge Deck Slabs Reinforced by Fiber Reinforced Polymers. *Aci Special Publ.* **1999**, *188*, 313–323.
16. Attia, K.; El Refai, A.; Alnahhal, W. Flexural Behavior of Basalt Fiber–Reinforced Concrete Slab Strips with BFRP Bars: Experimental Testing and Numerical Simulation. *J. Compos. Constr.* **2020**, *24*, 04020007. [CrossRef]
17. Ibrahim, M.; Ebead, U.; Al-Ansari, M. Life Cycle Assessment for Fiber-Reinforced Polymer (FRP) Composites Used in Concrete Beams: A State-of-the-Art Review. In Proceedings of the International Conference on Civil Infrastructure and Construction (CIC 2020), Doha, Qatar, 2–5 February 2020; Qatar University Press: Doha, Qatar, 2020; pp. 777–784.
18. Titirla, M.; Michel, L.; Ferrier, E. Mechanical Behaviour of Glued-in Rods (Carbon and Glass Fibre-Reinforced Polymers) for Timber Structures—An Analytical and Experimental Study. *Compos. Struct.* **2019**, *208*, 70–77. [CrossRef]
19. Prota, A.; Nanni, A.; Gaetano, M.; Edoardo, C. Selective Upgrade of Beam-Column Joints with Composites. In Proceedings of the International Conference on FRP Composites in Civil Engineering, Hong Kong, China, 12–15 December 2001; pp. 919–926.
20. Teng, J.G.; Yu, T.; Wong, Y.L.; Dong, S.L. Hybrid FRP–Concrete–Steel Tubular Columns: Concept and Behavior. *Constr. Build. Mater.* **2007**, *21*, 846–854. [CrossRef]
21. Hutchinson, R.; Tadros, G.; Kroman, J.; Rizkalla, S. Use of Externally Bonded FRP Systems for Rehabilitation of Bridges in Western Canada. *Am. Concr. Inst. ACI Spec. Publ.* **2003**, *215*, 239–248.
22. Gudonis, E.; Timinskas, E.; Gribniak, V.; Kaklauskas, G.; Arnautov, A.K.; Tamulenas, V. FRP Reinforcement for Concrete Structures:˙ State-of-The-Art Review of Application and Design. *Eng. Struct. Technol.* **2014**, *5*, 147–158. [CrossRef]
23. Titirla, M.D.; Ferrier, E.; Michel, L. On the Mechanical Behaviour of Innovative Moment Connections between Composite Floor Panels and Glulam Columns. *Int. J. Archit. Herit.* **2021**, *15*, 321–333. [CrossRef]
24. Kišicˇek, T.; Stepinac, M.; Renic´, T.; Hafner, I.; Lulic´, L. Strengthening of Masonry Walls with FRP or TRM. *J. Croat. Assoc. Civ. Eng.* **2020**, *72*, 937–953. [CrossRef]
25. Sbahieh, S.; Teymur, B. The Effect of Fiber Reinforcement on the Behavior of Cemented Sand.