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Review

Carbon Fibre-Reinforced Polymer (CFRP) Composites in Civil Engineering Application—A Comprehensive Review

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Abstract: In civil engineering, carbon fibre-reinforced polymer (CFRP) composites have emerged as a promising alternative to conventional materials. The article provides a comprehensive overview of the application of CFRP composites in various building structural elements and their characteristics and properties, such as their fatigue and corrosion resistance, stiffness and high strength, and incorporation of temperature factors. The advantages and disadvantages of CFRP composites and the current trends and prospects for CFRP composites in the construction sector are discussed. In addition, the article compares various studies on CFRP composites to shed light on their performance and potential limitations. This paper aims to provide useful information to researchers and practitioners interested in using CFRP composites in civil engineering applications. In addition, the article discusses emerging materials in CFRP, such as nanostructured carbon fibres, hybrid fibre reinforcement, and self-sensing CFRP. Additionally, the paper outlines how CFRP composites promote sustainability by increasing structural durability and longevity.

Keywords: civil engineering; CFRP composites; strength; stiffness; corrosion resistance; fatigue resistance; temperature factors

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

Academic Editor: Chenggao Li

Received: 14 May 2023
Revised: 2 June 2023
Accepted: 7 June 2023
Published: 12 June 2023

1. Introduction

Carbon fibre-reinforced polymer (CFRP) composites have recently gained popularity in different engineering applications, particularly civil engineering. CFRP composites are ideally suited for civil engineering structures due to their exceptional mechanical properties, high durability, and light weight. There has been a significant increase in the use of CFRP composites in the construction of bridges, buildings, and other infrastructure projects over the past few decades [1]. CFRP composites consist of carbon fibres woven together and then impregnated with a resin to create a strong and durable material. The carbon fibres provide high tensile strength, stiffness, and fatigue resistance, while the resin matrix protects against environmental factors such as moisture and ultraviolet radiation. The resultant composite material is light and has a high strength-to-weight ratio, making it ideal for structural applications [2,3].

An increased strength-to-weight ratio is one of the most significant benefits of CFRP composites. CFRP composites have a much higher strength-to-weight ratio than conventional construction materials such as concrete and steel. This means that CFRP composites can provide the same strength and durability as steel and concrete with less material, resulting in lighter and more efficient structures. This is especially advantageous in applications where weight is a determining factor, such as bridges and tall buildings. Durability is another advantage of CFRP composites [4]. The resistance of CFRP composites to corrosion and environmental degradation makes them ideal for use in harsh environments. In addition, they have a high fatigue resistance, which allows them to withstand repeated loading cycles without degrading [5]. This is especially important for bridges subject to constant movement and heavy loads.

Additionally, CFRP composites are highly adaptable, making them ideal for complex structures [6]. Carbon fibres can be interwoven in various patterns and orientations to produce a material tailored to specific structural requirements. This enables the creation of structures that are both durable and lightweight, as well as aesthetically pleasing [7].

One of the most important factors in CFRP composites' use in civil engineering is their usability in large-scale construction such as bridges [8] or buildings foundation [9]. Bridges are subjected to various loads and environmental factors, making them an ideal application for CFRP composites [10], strengthening existing structures [11]. CFRP composites can reinforce concrete and steel structures, increasing their load-carrying capacity and extending their service life. CFRP composites can also create lightweight, durable, and aesthetically pleasing bridge decks [12]. The beams reinforced with carbon fibre-reinforced polymer (CFRP) in geopolymer concrete (GC) subjected to load-deflection with and without stirrups were investigated by Mehdi et al. (2023) and adopted a bending test of the three-point method under similar conditions. The retrofitted GC beams have a greater capacity for load-carrying, deflection, and ductility than the reference beams without CFRP. The study's experimental and analysed data indicated that the impact of CFRP was more significant in terms of shear strength [13]. Figure 1 illustrates three distinct wrapping methods: side wrapping, U-wrapping, and complete wrapping in CFRP.

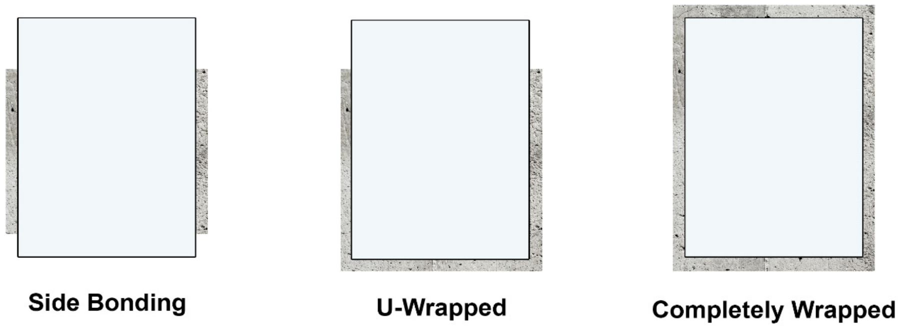

Figure 1. Three wrapping techniques for CFRP in concrete (from left): side, U-wrapping, and complete wrapping.

Pan et al. (2018) researched the morphology of magnesium (Mg) alloys and CFRP/Mg laminate alloys to assess their ability to resist galvanic corrosion, as well as their failure mode and interlaminate failure load. The study found that when the silicate is removed from the electrolyte, a pitted oxide film develops from the ceramic oxide film. This pitted film, present in CFRP laminates, significantly improved the peel strength by approximately 0.5 times compared to the oxide film and served as an admirable shield in terms of galvanic corrosion in laminates of CFRP/Mg [14]. Shen et al. (2022) analysed the CFRP grid by considering the cyclic behaviour in aspect ratio, reinforcement ratio, and reinforcement configuration. For this analysis, two reinforced concrete specimens, 13 concrete shear walls, and 11 grided samples with varying proportions of 1.01 to 2.20 are examined beneath the inverted loading. From the conclusion, it has been evident that the reduced aspect ratio will encourage ductility efficiently by 13.8% to 36% and show the finest stress distribution. Samples with the CFRP grid resemble reduced lasting distortion and increased displacement and load-carrying capacity in the concrete shear wall [15]. Sung Won et al. (2022) determined the reinforcement of compression in the bars of CFRP usage in RC columns by experimenting with 24 short columns subjected to elevated temperatures (0, 150, 300, and 450 °C) and concentric loading after the cooling of the column. The experimental result shows that the CFRP bars used in the column subjected to the elevated temperature show increased compressive resistance of 3 to 15% at a lower temperature of 150 °C, 7 to 13.6% at an increased temperature of 300 °C, and 50% at 450 °C [16]. Guo et al. (2023) conducted a study in which full-scale hollow RC box girders with different degrees of damage strengthened using CFRP with prestress of various levels were investigated regarding flexural behaviour. The study involved experiments and finite element analysis (FEA) [17]. Numerical simulations evaluated the flexural behaviour of the girders, including modes of failure, yield and maximum capacities, and deflections. Four box girders were tested. The hollow box girder, which had only minor damage and no reinforcement, served as a control specimen. The other three damaged box girders were reinforced with CFRP, with prestressing levels of 30%, 40%, and 60%, respectively. The findings indicated that the implementation of prestressed CFRP effectively enhanced the yield and ultimate capacities of the box girders. The study also revealed the remarkable strengthening effect of slightly damaged box girders reinforced with prestressed CFRP. CFRP is preferable to other FRP composites due to its superior tensile strength, elasticity modulus, fatigue strength, tensile strength, fire resistance, and chemical resistance. It is ideally suited for structural applications that require stiffness, rigidity, cyclic loading, tensile strength, fire resistance, and chemical resistance. With an improved strength-to-weight ratio, corrosion resistance, fatigue resistance, and customization options, CFRP has undergone significant development. It has found use in the construction of bridges, where it strengthens buildings, makes decks that are lightweight, and increases capacity for carrying loads.

The additional study must address several significant research gaps in the CFRP composites field. First, the long-term resistance to galvanic corrosion and performance of CFRP/Mg laminate alloys must be thoroughly evaluated. This research should consider various environmental conditions and optimise alloy compositions to improve resistance. Second, optimal design parameters and configurations of CFRP grids for various structural applications and loading conditions must be investigated. Examining a broader range of aspect ratios, reinforcement ratios, and reinforcement configurations can enhance the ductility, stress distribution, and overall performance of grid-reinforced CFRP structures. Finally, additional research is necessary to fully comprehend the behaviour of CFRP-reinforced concrete columns at elevated temperatures. This research encompasses various temperature ranges and loading conditions, allowing for a greater comprehension of mechanical properties, fire resistance, and durability. Eliminating these research gaps will significantly advance the knowledge and application of CFRP composites in civil engineering, developing more durable and dependable structures.

1.1. Material Properties of CFRP Composites

The exceptional material properties of CFRP composites make them suitable for various engineering applications. They have high tensile strength, rigidity, and fatigue resistance, are lightweight, corrosion-resistant, can be customised, and have excellent fatigue resistance. These characteristics contribute to the expanding use of CFRP composites in civil engineering applications such as bridge construction, structural reinforcement, and the creation of lightweight and resilient components.

Meizhong Wu et al. (2022) conducted a study to examine the static and fatigue shear behaviours of concrete beams with CFRP strips in place of steel stirrups. The results demonstrated that concrete beams with CFRP strip stirrups exhibit similar static shear behaviour to RC beams. Still, CFRP strip stirrups have superior fatigue life compared to RC beams, which significantly retards the onset of deflection, concrete cracks, and stirrup strain. Using CFRP strip stirrups can enhance the shear resistance of concrete beams under static and fatigue loading [18]. Honghan Dong et al. (2020) studied the corrosion damage caused by a hygrothermal environment to pile foundations. The CFRP-CFST pile is a composite structure comprised of external CFRP sheets and internal concrete-filled steel tubes. A system simulating a high-temperature, humid environment was designed to conduct corrosion experiments with these specimens. The mechanical properties and corrosion resistance increased when the concrete-filled steel tube was externally bonded to CFRP sheets, as determined by the test results. The experimental findings demonstrate that the CFRP-CFST pile is an effective method for protecting piles from corrosion and can be widely used for high-pile wharves in hostile environments [19]. Ananthkumar et al. (2020) investigated the effectiveness of composite materials, such as CFRP and GFRP, in preventing rebar corrosion. They used 300-mm-tall, 100-mm-diameter CFRP cylinders as a wrap and GFRP powder as an additive in concrete. The cylinders were subjected to 60 days of accelerated corrosion using a solution of 0.5 M HCl and 3% NaCl. The corrosion rate was computed, and the results indicated that CFRP and GFRP exhibited excellent corrosion resistance. The appropriate corrosion protection material is proposed [20].

1.2. CFRP Engineering Applications and Future Development in the Construction Industry

CFRP engineering applications and future development in construction and concrete will advance the industry. CFRP composites are used to reinforce, retrofit, and rehabilitate concrete structures, increasing their load-carrying capacity and durability. CFRP's lightweight construction potential makes high-rise buildings and long-span bridges more efficient and sustainable. Future development uses CFRP for unique configurations and innovative structural systems to create resilient and environmentally friendly infrastructure.

1. Construction firms increasingly use CFRP composites for structural reinforcement. They are widely used to strengthen and repair concrete bridges, columns, and beams. CFRP composites increase the durability of concrete structures by increasing load-carrying capacity, flexural and tensile strength, and durability;
2. Advanced retrofitting and rehabilitation techniques will advance CFRP construction. CFRP composites improve infrastructure performance and durability. Damaged structures can meet modern design requirements and withstand higher loads by externally bonding CFRP laminates or wraps to concrete elements;
3. CFRP composites make lightweight construction possible. Their high strength-to-weight ratio makes lightweight structures structurally sound. CFRP composites reduce dead loads on foundations and supporting systems, improving efficiency and sustainability. High-rise buildings and long-span bridges benefit from weight reduction;
4. Future advancements in CFRP in construction will involve investigating novel structural systems. Using CFRP cables, grids, and fabrics, novel structural configurations are created that optimise load distribution, increase structural stiffness, and improve overall performance. These innovative systems offer design flexibility, allowing for the construction of distinctive, visually striking structures with enhanced strength, durability, and sustainability;
5. CFRP construction's future is sustainable. CFRP composites reduce material and energy consumption and prolong the structure's lifespan, promoting sustainability. CFRP composites are lightweight, reducing transportation costs and carbon emissions. CFRP technology will help achieve sustainable construction goals and build resilient infrastructure as it advances.

1.3. Overview of CFRP Composites in Civil Engineering

This review article explores various uses of carbon fibre-reinforced polymer (CFRP) composites in civil engineering. It focuses on their usage in building structural components such as slabs, beams, shear walls, columns, etc. The article begins with an overview of the advantages and limitations of CFRP composites, including their increased stiffness and strength, resistance to fatigue and corrosion, and the influence of temperature factors on their performance. Additionally, the article examines the characteristics and properties of CFRP composites and compares the findings of various studies to provide a comprehensive understanding of their effectiveness in civil engineering applications. The article discusses current trends and future outlooks for CFRP composites in civil engineering. It provides insights for researchers and practitioners interested in utilising these materials in their projects.

1.4. Advantages and Limitations of CFRP Composites in Civil Engineering

Composites of CFRP are progressively used in the branches of civil engineering and structural uses. These materials offer a range of advantages and limitations that engineers and designers need to consider when selecting them for their projects [21,22]. Here are five key points to consider:

Lightweight: CFRP composites are incredibly lightweight and can offer up to five times the strength-to-weight ratio of traditional building materials such as steel or concrete. This makes them ideal for use in various structures and high-rises where weight is a concern.

Corrosion-resistant: CFRP composites have increased corrosion resistance, making them perfect for environmental use when subjected to corrosion and moisture elements. This makes them a good choice for bridges, marine structures, and other applications.

High initial cost: One of the significant restrictions of composites made of CFRP is their high initial cost compared to traditional building materials. This can make them cost-prohibitive for some projects, particularly those with tight budgets.

Brittle behaviour: CFRP composites can exhibit brittle behaviour under certain conditions, limiting their use in applications requiring high-impact resistance. Engineers must carefully consider the application and design for the specific use of the composite.

Limited fire resistance: CFRP composites can have limited fire resistance, limiting their use in specific applications. However, using specialised coatings and other treatments can help improve their fire resistance and make them suitable for more applications.

2. Types of FRP Composites Used in Civil Engineering

Fibre-reinforced polymer (FRP) composites are utilised in various fields of civil engineering because of their increased durability, greater corrosion, and strength-to-weight ratio [23,24]. Here are some common types of FRP composites adopted in civil engineering:

- Glass fibre-reinforced polymer (GFRP);
- Basalt fibre-reinforced polymer (BFRP);
- Aramid fibre-reinforced polymer (AFRP);
- Carbon fibre-reinforced polymer (CFRP).

CFRP composites have been chosen for review due to their widespread use in various civil engineering applications and their potential for future growth [25]. They are increasingly used in applications such as bridge repair and retrofitting, seismic strengthening, and reinforcement of concrete structures [26,27]. Their greater corrosion resistance, improved strength-to-weight ratio, and higher durability make them suitable for these applications [28]. However, their high initial cost and limited fire resistance must also be considered [29]. By reviewing the remarks on using CFRP composites in civil engineering, engineers and designers can better understand their potential benefits and limitations and make informed decisions about their use in their projects. Figure 2 details the various stages of connecting CFRP strips to concrete to enhance strength. Rui Guo et al. (2023) conducted a 403-day experiment on the accelerated ageing of a carbon/glass fibre-reinforced hybrid rod in deionized water at 40 °C, 60 °C, and 80 °C. The results demonstrated that hybrid rods' water absorption and diffusion behaviour conform to a two-stage model, with resin relaxation and interfacial debonding resulting in a decrease in interfacial strength and glass transition temperature. The plasticization effect is reversible with the removal of bonding water after drying, whereas the interfacial debonding is irreversible. Long-term life evaluation revealed that the interface shear strength of hybrid rod shells has a rapid degradation rate and reaches a stable level of 62%, making it the most important design parameter for bridges [30].

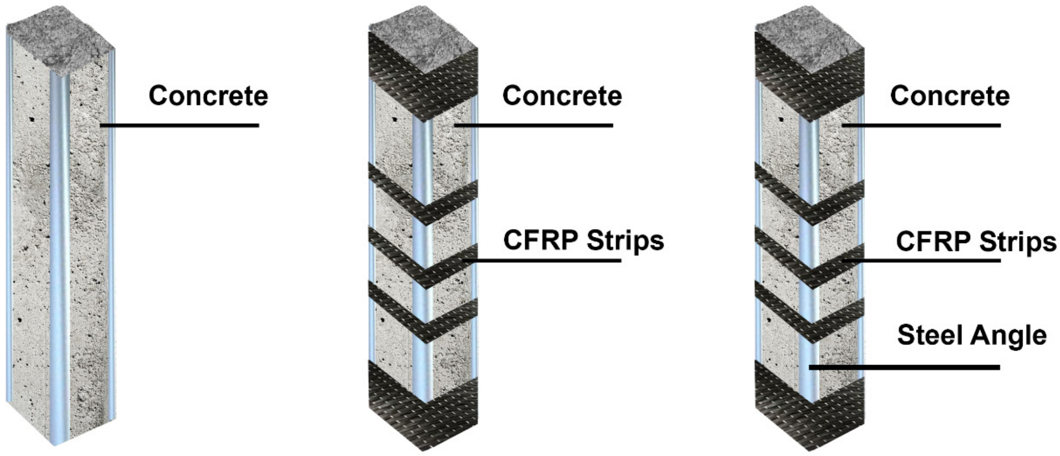

Figure 2. Stages of connecting CFRP strips to concrete for strength enhancement.

2.1. Carbon Fibre-Reinforced Polymer (CFRP) Composites

2.1.1. Application of CFRP to Buildings' Structural Elements

CFRP increasingly strengthens and rehabilitates structural elements such as slabs, columns, beams, and shear walls [31,32]. By adding CFRP to these elements, engineers can improve their capacity for load-carrying, durability, and seismic resistance while reducing their weight and thickness [33,34]. In this way, CFRP is helping to extend the lifespan of existing buildings and increase their safety and resilience in the face of natural disasters and other hazards [35,36].

Beams

In concrete beams, CFRP can be applied as external reinforcement or lamination to improve flexural strength and ductility; reduce the amount of conventional reinforcement required; and delay or prevent premature failure caused by corrosion or other forms of degradation. Ying et al. (2022) experimented with a new signal processing method to improve the damage diagnosis technique of detecting damage using a prestressed NSM CFRP beam transducer. It depends on the greater decomposition of the variational modal of the wavelet-tunable Q-factor transform [37]. An experiment shows that NSM CFRP beams and an analogue signal serve as studies on numerical cases to evaluate the proposed technique. The findings demonstrate that the ambient noise can be eliminated and the damage feature of the NSM CFRP beam can be separated using the variational modal of the wavelet-tunable Q-factor transform, which perfectly leads to damage assessment in the beam. Lu et al. (2022) investigated the peak deflection, failure pattern, and impact force peak value by using a drop hammer in a three-point bending test to determine the behaviour of impact in CFRP-strengthened RC beams (CFRP-RC beams) and reinforced concrete (RC) beams [38]. The developed strain crack was observed using a high-speed camera and the Digital Image Correlation (DIC) method. Varying the hammer height of impact and the bonding of CFRP in the beam leads to different outcomes regarding dynamic response and failure pattern. Thus, the crack will be decreased efficiently by adding CFRP to the beam, and impact velocity will be improved with the reduced inhibition effect. In Figure 3, the application of CFRP reinforcement to a concrete beam is demonstrated using adhesive bonding, which is intended to increase the strength of the concrete.

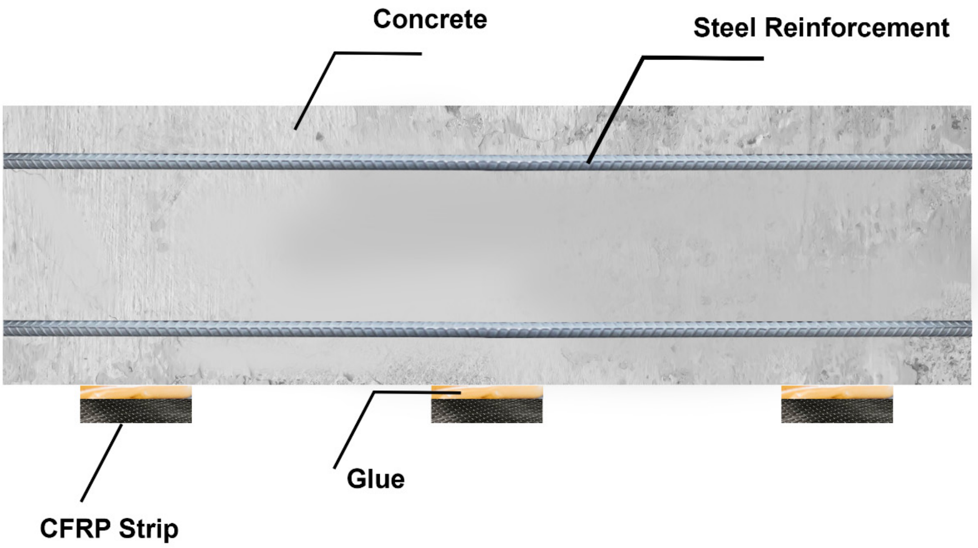

Figure 3. Adhesive bonding of CFRP reinforcement to concrete beam for improved strength.

Zhu et al. (2023) studied the CFRP-strengthened concrete beam using electromechanical impedance (EMI)-based monitoring of the interfacial performance by sustained loading and a wet-dry cycle test. The signal generated by EMI leads to changes in the interfacial performance under monotonic bending. Thus, the EMI method is effective even without EMI data [39]. Qiang et al. (2023) experimented with the three composite beams with two CFRP plates of 3 mm or 2 mm with a prestress of 15% or 10% using the test of 4 bending to determine flexure behaviour in steel composite beams. Before the analysis, the CFRP plate was under supervision for 100 h, leading to 3% strength usage from CFRP [40]. The analysed findings indicate that the CFRP of prestressed beams will significantly develop stiffness, ultimate load, and yielding load, and the ratio of beams strengthened is 80% at BS-1 and BS-3 under proper anchorage. Yu et al. (2022) suggested the bending failure mode using the data of 122 strengthened sheets of CFRP in non-corroded RC beams and 96 strengthened sheets of CFRP in corroded RC beams to evaluate the capacity of bending in the CFRP RC beam [41]. The corrosion degree-based and strengthening ratio-based approaches are suggested to determine the failures of four balanced and five failure modes. The result indicates the proposed failure mode calculation to help decide the bending failure and bending capacity of the RC beams with sheets of CFRP.

Wang et al. (2023) analysed the strengthening behaviour of CFRP-strengthened steel beams by adopting a three-dimensional finite model to encourage the mechanical response under a static four-point bending load [42]. A coded trapezoidal mixed-mode cohesive zone model (CZM) in the user subroutine ABAQUS of UMAT was used to design the failure of ductile adhesive in the strengthened beam using CFRP, and this method is found to be more efficient because of its increased stress distribution, fracture energy, and reduced stress. Guo et al. (2023) discussed the behaviour of load deflection, ultimate debonding, and load capacity by absorbing the 14 beams that contain 1 notched beam, 1 intact beam, and 12 CFRP retrofitted beams under varying temperatures of about 20 °C to 80 °C [43]. Bond slip behaviour was observed for different CFRP strain measurements, and the debonding load varies based on temperature change; that is, it decreased at 80 °C and increased for the temperature from 20 °C to 60 °C, and the energy of interfacial fracture reduced with the improvement of temperature. Liu et al. (2023) proposed the determination of the long-run behaviour of recycled aggregate concrete (RAC) beams with CFRP by adopting the finite element analysis method and evaluating the tendon relaxation, shrinkage, concrete creep, and tension stiffening [44]. The numerical evaluation was carried out depending on the superposition principle to assess the difference in strain and stress. The result shows that the long-term deflection in the RAC-CFRP beam can be reduced by improving the prestress load, and the axial shortening is the primary cause of deflection.

Jin et al. (2022) developed a 3D mesoscale simulation method to identify the failure mechanism of strengthened CFRP RC beams [45]. The stirrup and CFRP fibre ratios were introduced to determine the size effect and shear strength characteristics. The findings suggest that the increased ratio of the stirrup and CFRP fibre will increase strength gain, and the nominal shear strength will be reduced with the improvement of the section size. Huang et al. (2022) developed a ductility controllable device to predict the static and flexural behaviour by using drop weight impact and four-point bending in RC beams of end anchors of type H RC beams prestressed strengthened CFRP [46]. CFRP bars are used in place of reinforcement bars. The device indicates the ultimate resistance, ductility improvement, and overload indication. Multiple impacts were analysed based on the 3D non-linear finite model method. This method uses high-strength CFRP material effectively. Lam et al. (2023) studied the reinforcing methods against carbon fibre-reinforced polymer (CFRP) plate web buckling for steel beams [47]. The researchers used these four single-coped steel beams in the presence and absence of reinforced CFRP for experimental analysis. A CFRP plate can increase the load-bearing capacity, and the reinforcement effect is greatly effective with CFRP layers. It is analysed using a FEM model. Zhan et al. (2023) demonstrated the strengthening effect in conventional RC and CFRP-strengthened beams by adopting the quasi-static loading and drop hammer impact tests [48]. They evaluated the residual load-carrying mechanism based on a high-resolution explicit tool. The findings show that the CFRP sheet will decrease damage in the beam mid-span, residual displacement, and the removal of impact damage. The presence of CFRP will reduce the impact of post-impact energy absorption, residual stiffness, and resistance. The beam can be affected by the greater impact energy.

Hasan et al. (2023) investigated the hybrid method of shear-deficient RC beams to determine the consequences of curing. The shear capacity was reduced by strengthening the beams with CFRP [49]. Thus, the complete coupling of the beam using CFRP will improve the beam's shear performance effectively. Depending on the shear and bending tests, a design strategy was developed to adjust the RC bridge corrosion. Alabdulhady et al. (2022) analysed eight RC-supported beams with one layer of CFRP based on flexure load to determine the failure mode mechanism, stiffness, load carrying capacity, and flexural behaviour with varying strength of compression (fc) of 21.10, 36.10, 48.20, and 68.50 MPa to describe the reduced, normal, and increased strength [50]. The result indicates that the compression strength in concrete was inversely proportional to the CFRP behaviour. The comparison of experimental and ACI 440.2R-17 was within ±16%, respectively.

Using CFRP composites, Lokman Gemi et al. (2019) strengthened prefabricated purlins against shear damage caused by vertical loading. The failure mode of the CFRP-reinforced purlins was dominated by bending damage, and, depending on the CFRP wrapping, the vertical loading capacity was increased by up to 59%. Damage analysis was also performed on the CFRP composite [51]. Yasin Onuralp et al. (2021) investigated the behaviour of prefabricated concrete purlins (PCPs) through numerical modelling using the finite element programme ABAQUS. The parameters longitudinal steel reinforcement ratio, shear friction reinforcement ratio, bending reinforcement ratio, suspension reinforcement ratio, concrete and steel mechanical properties, pre-stressing level, CFRP ply orientation, the number of CFRP plies, and CFRP composite material properties were chosen. Compared to the effects of the parameters related to CFRP, the results of the parameters related to reinforced concrete were found to be minimal. The general FRP layout is proposed to delay or prevent shear cracks in the beams, and numerical analyses validate the proposed layout [52]. Ceyhun Aksoylu et al. (2020) utilised two CFRP applications to reinforce circular-holed shear-deficient beams. The results demonstrated that a D/H ratio of 0.30 decreased load-carrying capacity while increasing ductility. Various configurations of CFRP enhance load-bearing capacity and ductility. At a D/H ratio of 0.64, no CFRP-based strengthening option was effective [53]. Pultruded GFRP composite beams infilled with hybrid fibre-reinforced concrete under four-point loading are analysed experimentally, analytically, and numerically in this work. Experimental variables included pultruded GFRP box profiles, conventional steel bars, hybrid bars, and externally wrapped GFRP. Always use hybrid reinforcements [54,55]. Yasin et al. (2022) examined reinforced concrete beams with circular holes and CFRP-strengthened failures [56,57]. Gemi et al. (2022) examined CFRP-reinforced, shear-deficient, under-balanced reinforced concrete beams with rectangular cross-sections. The ideal strip for wf/sf was defined by rules, but the beam needs to reach 0.82 to attain sufficient shear reserve value [58,59]. Emrah Madenci et al. (2023) examined the elastic properties of textile-based composites with carbon nanotube (CNT) additions. CNT enhanced axial tensile force and bending capacity in experiments, whereas MWCNT raised tensile modulus by 9% [60,61]. The study examines how wrapping the composite beam affects the reinforced concrete beam's shear strength and load deflection. Three-point and four-point loading evaluated nine hybrid beams with varied shear span-to-depth ratios. The composite beam's ductility and strength were greatly improved by the GFRP wraps, which reached beam depth-related levels [62,63].

Columns

The load-bearing and ductility capacities of any structure improve by using CFRP to wrap around the concrete column [64]. This technique enhances the composite material's ability to resist failure and cracking, resulting in a more robust structure [65]. Tang et al. (2022) accompanied the theoretical and analysed determination of axial compression of a concrete-filled double-skin tube (CFDST) stub column curbed with carbon fibre-reinforced polymer (CFRP) with the stainless-steel outer tube [66]. The result depends on comparing the evaluation conducted for the CFRP-curbed CFDST and the square CFDST. In conclusion, it has been proven that the increase in CFRP layers will result in an improvement of 17% in the ultimate bearing capacity of the column. Additionally, a new method based on the twin shear unified strength theory and method of limit equilibrium was suggested to forecast the bearing capacity. Li et al. (2022) described the characteristics of bending and compression by different load eccentricity and slenderness ratios in nine specimens of CFRP-strengthened square concrete-filled steel tubular (SCFST) composite columns [67]. They compared them with SCFST columns without CFRP. The investigation was conducted regarding various aspects such as strength reduction factor, moment-curvature response, longitudinal strain response, peak load, and failure mode. The result is then verified with various existing design approaches, such as the empirical equation, GB50936, and the AISC-LRFD. From the investigational analysis, it has been concluded that the design approach based on GB50936 gives a more accurate value than the other two methods. However, it also shows that this method does not apply to columns with a higher slenderness ratio. The result indicates that improved energy dissipation will lead to an increased ultimate bearing capacity of SCFST-CFRP as compared to that of the SCFST column.

Tang et al. (2023) determined the compression behaviour of a CFRP-curbed concrete-filled double-skin stainless-steel tube (CFDSST) stub column by evaluating the strain response and axial load shortening curves [68]. Typical failure modes were identified by developing the FE model along with the experiment, and the comparison was made with CFDSST without CFRP. The study found that CFRP-imposed CFDSST will efficiently enhance compression behaviour and local buckling restraint compared to CFDSST without CFRP. A proposed model was also suggested based on the principle of superposition to examine the ultimate bearing capacity. This model has been proven to accurately predict the ultimate load. Zhou et al. (2023) experimented with the impact resistance behaviour by comparing the cantilever columns made of RC and CFRP grid-reinforced engineered cementitious composites (ECC) columns [69]. Dynamic behaviour was developed in ECC by using the continuous surface cap model (CSCM). The parametric examination was conducted based on horizontal impact loading and showed that the CFRP grid-reinforced ECC was prone to lower shear failure than the ECC curbed column and had increased shear capacity compared with the RC column. Figure 4 shows how CFRP reinforcement can enhance the strength and durability of concrete columns, increasing their load-carrying capacity and resistance to external forces.

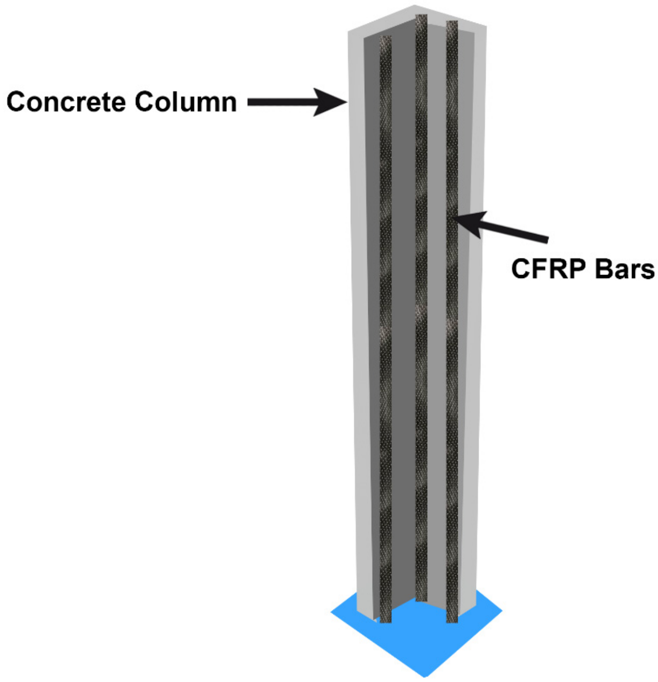

Figure 4. Enhancing strength and durability of concrete columns through CFRP reinforcement for increased load-carrying capacity and resistance to external forces.

Samy et al. (2022) experimented with the load-carrying capacity of a rectangular and square column by adopting a new strengthening technique that enriches the CFRP jacket efficiency covering the column [70]. This 13-column specimen was analysed for varying profile and shape of cross section based on the varying radius of 10 mm, 20 mm, and 30 mm, increased load carrying capacity of 35%, 54%, and 80% with a varying ellipsoidal profile of 10 mm to 30 mm, and increased CFRP jacket by 12%, 29%, and 50%. In conclusion, it has been found that the traditional method of covering the column will increase efficiency by 60%. In contrast, the new technique of CFRP jackets will increase efficiency by 80%. Cao et al. (2023) studied the buckling properties of CFRP strengthened. High-strength steel (HSS) welded T-section column [71]. A sample of an 800 MPA column of T-section HSS welded from six specimens was analysed for axial compression by considering the three crucial factors: width to the thickness of the plate, count of CFRP layers, and slenderness of column. The bearing capacity FE model was described using the ANSYS software for analysis. From the results, it has been concluded that the CFRP layer will successfully decrease the flexural deformation by 56.5%, the torsional deformation by 90.4%, and local buckling of the specimen. The capacity of the bearing of the sample will increase by 21%, 27.6%, and 31.5% for one, two, and three layers of CFRP, respectively. Tan et al. (2023) inspected the flexural strength of the RC column by attaching the prefabricated plates of CFRP vertically and a concrete jacket around the column [72]. Cyclic loading was applied to five different samples to determine the strain distribution, and the cyclic performance of the column was strengthened using CFRP vertical plates. The result shows that the specimen without CFRP will show a two-times lower cracking load and fail in the compression area by developing the plastic hinges compared to those with CFRP. It has been declared that load-carrying capacity will increase by 17% and 15% based on 2-layer and 1-layer CFRP plates attached to the column compared to the standard column, respectively.

Chen et al. (2022) experimented with the axial compression behaviour test of the CFRP steel tube column with 18 specimens, including the nine that contain the CFRP internally, based on the factors of number and position of CFRP [73]. Samples of 139 axial compressions were gathered and analysed to determine the equation, and a FEM model was created to compare the results of the equation. The analysis proved that 7.3%, 12.55%, and 10.6% increased the ultimate load capacity of the specimens with the growing count of CFRP layers. Mohammed and Abebe (2022) determined the finite element analysis (FEA) for determining the blast resistance for RC columns confined with CFRP and the standard RC column [74]. Studies have been carried out in terms of considering the reinforcement detail schemes, the height of bursts, concrete compressive strengths, 0/90 CFRP-strengthened RC columns, and standoff distances. From the result, it has been identified that the smaller the scaled distance, the larger the lateral displacement and failure of shear, and the increase of layers of 0/90 CFRP will result in a smaller blast.

Rodriguez et al. (2021) experimented with the beam-column connection using two different beam-column joint systems. Initially, it was tested without damage [75]. Later, two rehabilitation techniques were conducted using ultra-high-performance mortar with steel fibres and carbon fibre-reinforced polymer connected externally. Various loadings were used to detect load-deformation capacity in terms of equivalent viscous damping, drift capacity, energy dissipation, cracking, and visual damage. The findings show that in columns C1 and C2, the capacity of load carrying developed after rehabilitation by around 15% and 20%, followed by decreased ductility ratios in 21 and 30% of the specimens. For the equal drift ratio, the damage indices were found to be low; for the 3% ratio, the damage indices were found to be 0.68 for rehabilitated specimens and 0.94 for real specimens. Xiaong et al. (2023) studied the ultimate and yield capacity of the concrete-filled steel tubes (CFST) stub columns of preloaded circular columns strengthened with CFRP [76]. Forty-eight models were assessed for parametric study to obtain the accuracy and reliability of the sample by comparing the FE model analysis and theoretical equation with the experimental results, and it was identified that the effectiveness of strengthening is greater for ultimate strength and lower for yield strength when the CFRP is used to strengthen the precast CFST stub column.

Slab

CFRP can enhance the flexural strength and structural integrity of concrete slabs by bonding them to the underside, thus reducing deflection [77]. Türer et al. (2023) analysed the performance of CFRP strips in strengthening flat slabs by considering the strain behaviour, energy dissipation capacity, maximum bearing capacity, and initial stiffness as the parameters [78]. They developed a model using ABAQUS; for this, nineteen slab samples were created to determine the position and size, placed adjacent to the column, and strengthened using CFRP strips with fan-type anchors. After the analysis, the load-carrying capacity was improved by 50% in the presence of anchored CFRP strips. Zhou et al. (2023) determined the usage of CFRP sheets and a self-locking device to strengthen the RC slab at the end anchorage to arrest the deboning [79]. A four-point bending test was performed for six one-way RC slabs with CFRP bonding, which leads to increased ultimate load and the bonding being improved efficiently by 46% by adopting the hybrid anchored (HA) CFRP method of strengthening. With the increased length of the bond, the usage of the CFRP rate will fall to 28%, and it requires more examination in cases of strengthening with CFRP sheets.

Yazdani et al. (2021) experimented with the enactment of prestressed self-consolidating concrete (SCC) slabs that are reinforced with carbon fibre-reinforced polymer (CFRP) sheets [80]. Factors such as energy absorption, force-deflection curves, and cracking behaviour were considered for this study. The analysis shows that the presence of a single CFRP layer sheet will improve energy absorption and flexural strength by 71% and 30%, respectively, and decrease the width of the crack by 23%. In contrast, using two-layer CFRP will not effectively perform in the case of flexural capacity. When there is an improvement in the eccentricity ratio, the load-bearing capacity also improves by 80%. Thus, the findings suggest combining a single CFRP layer improves ductility, load-bearing capacity, and deferred deboning because of less tensile strain and cracking. Azevedo et al. (2022) determined the fire resistance of reinforced concrete (RC) slabs analysed with carbon fibre reinforced polymer (CFRP) strips by using three various methods: continuous reinforcement embedded at the ends (CREatE), externally bonded reinforcement (EBR), and near-surface mounting (NSM) and compared the results obtained [81]. The CREatE method shows greater fire resistance for about 24 min than EBR with 2 min and NSM with 16 min without protection. The critical temperature of glass transition varies based on the modulus curves for CREatE, NSM, and EBR as 3.0 Tg, 1.0 Tg, and 2.5 Tg, respectively. The depiction in Figure 5 shows how CFRP reinforcement can be used in slabs to improve the capacity of load-carrying, prolong the service life of existing structures, and enhance the performance of new ones.

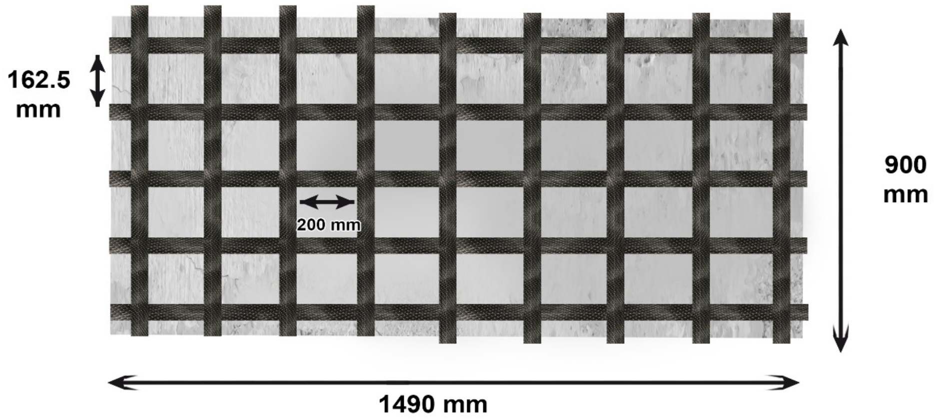

Figure 5. Application of CFRP reinforcement in slabs.

Yang et al. (2023) experimented with the resistance to blast in the presence of CFRP-strengthened RC structures depending on the coupled Lagrange–Euler (CLE) method [82]. Parameters such as charge weight, retrofitted scheme, retrofitted material, and retrofitted were considered to determine blast resistance ability in the air-baked slabs retrofitted with CFRP. The analysis suggests that the present CFRP will reduce the flying debris and deformation in the underwater explosion, thereby showing better blast resistance. Assad et al. (2022) experimented with the numerical method that arouses the fire by using two various methods, namely externally bonded (EB) and near-surface mounted (NSM), and compared the experimental data derived by using a three-dimensional non-linear finite element model (FE) to verify the structural and thermal behaviour of the RC slabs with CFRP [83]. From the analysis, it has been identified that the NSM method indicates the best result in terms of fire resistance and static loading, with an improvement of 15% of the ultimate load compared with the EBR method.

Bielak (2023) presented a test setup to determine if the dowel behaviour of CFRP grids matches the real method, and the impact of pre-strain, pre-crack width, and shear crack in the tension region based on the effective area was analysed [84]. Based on the test setup, the conclusion has been drawn that the major load will depend on the formed crack pattern. Ghayeb et al. (2023) studied the influence of using CFRP sheets in the tension region of two-way RC slabs [85]. Punching shear was developed using the static load in the strengthened and unstrengthened slabs. The test result shows that the sample with a CFRP-strengthened slab offers better shear resistance, increased ductility and load displacement, and increased punching capacity. The presence of CFRP will improve the ultimate strength by 30% and the ductility by 50 to 73% compared to the sample without CFRP. Breveglieri et al. (2021) analysed the RC structures in the laboratory and the environmental exposure method [86]. In the outdoor method, prestressed slabs with CFRP strips and non-prestressed slabs were kept in the environment for four years. The same has been tested in the laboratory for a certain period to determine the ultimate slab strength. From the analysis of the two observations, it has been observed that long-term exposure does not impact the capacity of the strengthened slab to carry loads.

Alrousan and Alnemrawi (2022) analysed the reinforcement performance of the bridge's deck under the consequences of reinforcement with CFRP and ASR damage [87]. The NLFEA technique is used to predict the experimental data with reinforcement ratios

(0.38, 0.46, and 0.57%) and the stages of first, second, third, and without ASR damage. From the technique, it has been found that the ratios of 0.38% and 0.46% will result in increased capacity of load carrying, durability, and serviceability, a reduced rate of 2 and 3 levels of ASR damage, and a linearly reduced relation between the ASR level and the energy of the slab.

Shear Wall

Bonding CFRP to the surface of shear walls can enhance their resistance to seismic forces, shear capacity, and stiffness, increasing safety and durability [88]. Shen et al. (2022) inquired about the distortion action of concrete shear walls by adopting a method depending on the uniaxial shear-flexure model (USFM) [89]. By using this method, it has been found that there is increased lateral load due to the variation between cyclic and monotonic loading, with a varying peak load from 4.9% to 10.8%. The new suggested method accurately identifies the peak load point, strength, initial stiffness, and displacement response. The result indicates that the flexural component shows 65% failure of total deformation compared to the slip and shear components, and further analysis is required for the other components. Sahebjam and Showkati (2016) examined the effect of polymer fibre by applying quasi-static cyclic loading to perforated carbon fibre-reinforced polymer–steel composite shear walls [90]. Four single-bay and single-story perforated shear walls and three composite shear walls with an aspect ratio of 1.33 and varied fibre direction were analysed by considering the ductility, load-carrying capacity, and stiffness by a hysteresis curve. The curve shows that the fibre in the tension area will affect the factors of stiffness and ductility but neglect the fibre orientation.

El-Kashif et al. (2019) determined the shear behaviour of RC shear walls undergoing lateral load by adopting the FEM in ANSYS [91]. A model of seven walls from two specimens was developed and investigated using reverse cyclic and monotonic loading to set the concrete confinement, ductility, strength of flexure, and shear capacity. The result shows that using fibre-reinforced polymer (FRP) material will efficiently remove the shear failure caused by its brittle nature. Comparing experimental and numerical results will lead to a similar conclusion.

Altin et al. (2013) discussed the shear deficiency in RC walls on hysteresis behaviour by adopting one specimen without retrofitting and four samples with retrofitting along with CFRP strips of aspect ratio 1.5 and testing based on the parallel strip, horizontal, and X-shape to increase the ductility and strength [92]. From the analysis, the horizontal stripes contribute to the development of plastic hinges because of flexural hysteresis, and the X-shape indicates an unsuccessful premature shear wall. Using CFRP strips increases displacement capacity and limits shear crack development. Hatami et al. (2012) experimented with the non-linear shear behaviour of composite steel shear walls reinforced with carbon fibres (CSSW) and steel shear walls (SSW) [93]. The properties of fibre content and panel width were investigated both experimentally and numerically. The findings suggest that the increased fibre will lead to higher stiffness, carbon absorption, capacity, and strength with reduced ductility values and a greater influence on SSW.

In contrast, a wider panel width will improve CSSW and SSW behaviour. Yu et al. (2023) experimented with bolted connection laying in CFRP steel composite shear wall by adopting the cyclic load on samples of two 1/3-scale steel plate shear wall (SPSW) and related them to the pure SPSW by finite element analysis to determine energy dissipation capacity, stiffness, and the bearing capacity of ultimate and found them to be higher by 4.2%, 7.7%, and 23% [94]. The aspect ratio, CFRP layer, and angle orientation were identified and calculated. The suggestion indicates that the improved angle orientation increased the capacity of energy dissipation and ductility. The aspect ratio to be used should lie between 1 and 1.5 for the CFRP composite shear wall.

Meftah et al. (2006) determined the seismic analysis of 20-story RC coupled shear walls subjected to 3 earthquakes with varying fibre [95]. Adhesives and adherents are used as shear wall members and are analysed using the mixed finite element method. The lateral deflection due to fibre arrangement leads to dynamic behaviour change, which is also analysed in the RC coupled shear wall. Furthermore, an investigation is required to strengthen the RC couple shear wall. Huang et al. (2020) analysed about six shear walls in which one of the wall sample is a wall of RC reinforced with steel and the rest is a CFRP-reinforced grid in the horizontal and vertical configuration under various factors such as reinforcement configuration, aspect ratio, and horizontal reinforcement ratio with various cyclic loadings [96]. This specimen undergoes compression diagonally, and the aspect ratio ranges from 1 to 1.4. The result shows that the horizontal CFRP grid arranged horizontally indicates increased concrete confinement, decreased deformation, and increased shear resistance. A model named Truss Arch was created to determine the shear capacity of the CFRP gridded shear wall.

Yu and Zhu (2023) developed a composite sandwich plate specimen made of polyethene terephthalate (PET), steel plate shear wall (SPSW), and carbon fibre reinforced polymer (CFRP) and compared it with non-stiffened traditional SPSW for hysteresis behaviour and the mechanism of failure by performing the quasi-static test [97]. The comparison suggests that the sandwiched plate's stiffness and energy dissipation are improved by 34% and 38.44% for the drift load of 2%, respectively, and the plane deformation decreased by 93%. Thus, the sandwiched CFRP corrugated plates provide a better anti-buckling position.

3. Characteristics and Properties of CFRP Composites

3.1. Durabilityh of CFRP

3.1.1. Corrosion Resistance

CFRP is a corrosion-resistant material due to its inert properties, high strength, and resistance to harsh environments [98]. Wrapping CFRP around corroded structures can enhance their durability and lifespan, reducing the need for costly repairs and replacements [99]. Karim et al. (2020) conducted a 13-week salt spray corrosion test to identify the effectiveness of various rivet Zn-Ni and Almac coating types in corrosion behaviour and the degradation of joint strength in CFRP/Aluminium joints [100]. The experimental result shows that self-piercing rivet (SPR) joints with Zn–Ni-coated joints will deliver three times lower strength losses when compared with Almac-coated joints, increasing the corrosion resistance more effectively than that of Almac. Huang et al. (2023) experimented with the bonding behaviour of concrete and corroded steel with CFRP cathodic protection [101]. Tests have been conducted considering the bond performance and three ICCP current densities, including linear polarisation, pull-out, induced current cathodic protection (ICCP), and accelerated corrosion tests. The experimental result indicates a gradual increase in bond strength by 20% with a decrease in the ratio of pre-corrosion by 50.7% and ICCP current density. Shao et al. (2023) studied the characteristics of horizontal bearing and the life and durability of the CFRP composite piles [102]. For this, the durability stage is separated into the starting stage of reinforcement corrosion and the propagation of the crack. It is analysed using the Monte Carlo simulation method and chloride diffusion model, whereas thick-walled cylinder theory is used to identify the concrete cracking layer. With a different ratio of replacement mode, a pile bending test is carried out. Findings show that for CFRP composite piles, the lower the reduction ratio, the higher the replacement ratio of flexural stiffness. Meanwhile, when there is an increment in the replacement ratio of CFRP reinforcement, there will be a decrement in the shear force and the moment of pile bending.

Ren et al. (2022) researched the fatigue properties and mechanical effects of aggressive corrosion in CFRP strand sheet/steel double strap joints with different bond lengths [103]. By adopting a quasi-static tensile protocol, the specimen is exposed to the environment for 24, 48, and 72 h, and the bond strength, stiffness, and ultimate tensile strength are calculated. The analysis showed that there is an increment in fatigue performance and a reduced rate of corrosion with the presence of an increased length of the bond. The specimen exposed to 72 h in the corrosive environment with improved bond length leads to improved strength of 11% and stiffness of 14%, which are higher when compared with 24 and 48 h. observation.

Wu et al. (2021) discussed the properties of glass fibre sheets (GFS) on the bond between CFRP and steel and their corrosion behaviour [104]. Experimental tests such as fatigue, a static test to determine the bond behaviour, and an accelerated corrosion test to assess the efficiency of GFS were conducted in three different types depending on the presence and absence of the GFS. The result suggested that the GFS declined the fatigue bond performance and increased the behaviour of the static bond, which led to the presence of GFS as an adhesive layer that will reduce galvanic corrosion in the CFRP steel bonding.

Hu et al. (2022) used carbon fibre-reinforced polymer (CFRP) for its better electrochemical and mechanical properties as an anodic component in impressed current cathodic protection (ICCP) [105]. Measurement of electrochemical properties was conducted for 19 RC cylinders in terms of ICCP densities of current (5, 20, and 80 mA/m^2) degrees of pre-corrosion (3%, 6%, and 12%) by using different methods of protection such as CFRP wrapping, epoxy coating, and non-protection. It has resulted in ICCP and CFRP wrapping being much more efficient than epoxy coating for the suitable current density. For the pre-corroded sample of 3%, the density of current is 5 mA/m^2 and for 6 and 12% of the pre-corroded sample, 20 mA/m^2 is optimal. Thus, CFRP wrapping could decrease the transmission path of steel and increase corrosion resistance by thickening the concrete core.

Chen et al. (2022) discussed the mechanical and corrosive behaviour of riveted joints and CFRP/aluminum stacks using the cyclic salt spray test [106]. Joints are subjected to an environment conducive to corrosion for four weeks. It was found that when there is a development of interfacial corrosion in CFRP/Al stacks, there is a gradual decrease in failure displacement of around 14 mm with a 3% reduction in maximum load, which shows the behaviour of durability and corrosion in the rivet joints of CRP/Al stacks. Wang et al. (2022) experimented with three samples that included a chloride attack of 2 years in combined piles of RC (AC piles), CFRP-bonded RC piles (CP piles), ordinary piles of RC (UC piles) for detecting the free ion chloride concentration (Cf) profile [107]. For this, the indoor test was conducted by creating a marine simulation system, and the piles were tested using a numerical model depending on Fick's II law. The result shows that the Cf of ordinary RC piles will be higher than that of CFRP-bonded piles, which has a positive effect on decreasing the chloride content and sheltering the pile from external chloride attack. Sou et al. (2021) studied mechanical degradation in CFRP/Al bolted joints with epoxy and PVC film corrosion protection [108]. The specimen is exposed at 30 degrees Celsius to a 3.5% sodium chloride solution for about 0 to 8 weeks. Double-lap bearings and material were analysed using a step profiler and micro-CT. From the analysis, it has been concluded that the epoxy coating joints show more favourable protection as that PVC film shows more failure at joints and thus results in the epoxy coating being a better protective covering with less deterioration to damage.

3.1.2. Fatigue Resistance

Mohabeddine et al. (2022) suggested a new approach based on fatigue cyclic degradation to determine the life of fatigue in CFRP-bonded retrofitted metallic detail patches [109]. Degradation of the fatigue cycle was considered for the new fatigue damage accumulation model approach. As per the new approach, it has been identified that the increased stress level led to a decreased extension ratio because of the effect of fatigue loading. These approaches can be used effectively using the finite element method. Doroudi et al. (2021) experimented with numerical and practical strategies for determining the behaviour of CFRP-cracked steel plates under crack loading [110]. Four CFRP-strengthened specimens and one cracked steel specimen without CFRP were analysed for the conduct of fatigue in terms of CFRP-to-steel bonded joints, fatigue-life extension, and failure modes under the loading of fatigue behaviour. The CFRP-strengthened plate shows higher fatigue life depending on the developed bond slip model than the specimen without CFRP.

Gadomski and Pyrzanowski (2016) discussed the difficulty in finding the CFRP structure deformation at the fatigue destruction timing, leading to the decrement of structure stiffness [111]. The moment has been analysed for this analysis, which gives an inappropriate result. A new approach based on the electrical resistance has been suggested by measuring it under varied static and periodic load conditions. The bending moment, eight voltages, and centre deflection of the probe were determined. As per the experimental and numerical conclusions, the change in electrical resistance gives the best result in CFRP fatigue destruction of structure compared to the bending moment. He et al. (2022) studied the failure mechanism and fatigue behaviour in CFRP/Al single-lap joints depending on the digital image correlation (DIC) system to record the fatigue process [112]. Under varied reliabilities, fatigue behaviour was discussed based on the well bull distribution theory. It was found that the bonding portion stiffness in the lap joint is four times greater than that of other parts. A crack was initially developed at the Al lap end with 70% and 50% stress levels, and the stress level was reduced with the increment of adhesive failure proportion.

Li et al. (2022) inspected the fatigue properties of CFRP plates [113]. The experiment utilised four kinds of stress fatigue and strengthening configurations at five different levels of corrosion damage in terms of crack propagation, fatigue fractography, and fatigue life. The result shows that the presence of CFRP will increase fatigue life and decrease crack growth in the corroded steel plates. The development also leads to an extension of fatigue greater than 85.3 times in the corroded steel of the unpatched plate and two times in the uncorded steel plate. Li et al. (2022) presented the experimental and theoretical analysis of flexural behaviour, loss on prestress, and interfacial stress of obtaining prestressed carbon fibre reinforced polymer (CFRP) used in steel structures by applying 25% prestress with a solution of 3.5% NaCl in the sample [114]. It has been proven that prestressing CFRP will suspend the bonding at the interface by decreasing the interfacial stress, resulting in a reduction of loss due to prestress of 2.7% in the sample subjected to wet/dry cycles (WDCs).

Lesiuk et al. (2017) experimented with fatigue cracks by comparing CFRP patches in the beam of mild-rimmed steel and puddled iron used 100 years before [115]. A hybrid approach was suggested for determining the fatigue crack based on energy dissipation. It has been evident that the growth of fatigue increases in the steel used earlier compared with the modern steel. The suggested approach results in the use of CFRP for strengthening the fatigue crack, which is appropriate for old structures, and further investigation is required to evaluate the optimal conditions of the CFRP patches.

Vavouliotis et al. (2011) determined the fatigue loading effect in quasi-isotropic carbon fibre-reinforced laminates (CFRs) by absorbing the electromechanical response [116]. The epoxy matrix with multi-wall carbon nanotube (MWCNT) was examined and related to epoxy CRP at three stress levels. These are then associated with acoustic emission and stiffness degradation to predict the occurrence of damage. The presence of a characteristic damage state (CDS) associated with electrical resistance leads to a reduction in stiffness, initially indicating the rest of life independently from the applied stress level and showing an increased confidence coefficient (R2). Kotrotsos et al. (2023) determined the behaviour of delamination on fatigue resistance in the CFRPs by adopting two modes (Mode I and Mode II) under different loading conditions and adopting the fatigue onset life test based on Paris Law with varied displacement and constant amplitude [117]. From the investigation, it has been shown that the BMI resin-modified CFRS offers better resistance against the delamination that occurs.

3.1.3. The Incorporation of CFRP in Temperature Factors

CFRP is known for its excellent thermal conductivity and low thermal expansion, making it a valuable material in temperature-sensitive applications [118]. Adding CFRP to structures exposed to extreme temperatures can reduce thermal stress, enhance stability, and improve overall performance [119]. Li et al. (2023) studied the moisture–heat coupling effect in nano-SiO_2 adhesive specimens and the CFRP-steel lap joint bonding using scanning electron microscopy (SEM) [120]. Due to the increased ageing in a 25 °C water bath, the adhesive glass transition temperatures (Tg,s, Tg,t) became reduced because of the variation in the temperature. The reduced effect of bonding occurs due to the reduction of shear s73 strength. Once the water bath is carried out, the interface toughness is reduced, reducing shear stress transfer. Al-Abdwais and Al-Mahaidi (2022) experimented with the effectiveness of modified compendious material to withstand the load at increased temperatures depending on the presence of CFRP reinforcement [121]. The beams are tested under constant service loads and elevated temperatures until failure occurs. These are then compared with the numerical value. The analysis shows that the epoxy adhesive will perform less well than cementitious adhesive at an increased temperature.

Yoo et al. (2022) determined the bond strength in ultra-high-strength concrete (UHPC) with CFRP and compared it with residual steel bars [122]. A 150 mm × 150 mm × 150 mm specimen was tested at elevated temperatures of 150 °C and 250 °C and at ambient temperature. The findings show that increased thermal temperature leads to decreased bond stress. Bond strength improved by 9% when subjected to a 250 °C temperature that was elevated. After analysing the experimental results with the CMR model and the BPE model, the bond-slip is increased in CMR than in BPE, indicating that the bond stress of residue in CFRP bars in UHPC meets the requirements mentioned in ACI 440.6 M after heating. Wang et al. (2023) determined the analytical solution for debonding CFRP to the steel/concrete interface to detect the thermal effects based on thermal and mechanical loads [123]. The proposed analytical solution is examined for CFRP thickness, CFRP elastic modulus, and thermal effects with four different forms of experimental data. The conclusion shows that the suggested solution effectively determines the response of debonding. The bond length is strongly linked to thermal effects when using stiff and thick CFRP materials to strengthen the concrete. Kaiser et al. (2022) discussed the failure mechanism and mechanical performance at different temperatures, such as elevated temperature, cold temperature, and room temperature, of titanium adhesive tubular lap joints (TLJs) and thin-walled CFRP [124]. Experimental design, a static tensile test, and finite element analysis were conducted to detect the damage mode in detail. The findings show that at elevated temperatures, a failure and the delamination of CFRP that occurred at the inserted end are formed because of shear stress when titanium deformation occurs. Thus, the adhesive bond damage mechanism's behaviour is affected majorly at high cold and hot temperatures.

Peng et al. (2023) evaluated the specimens of three concrete-filled square steel tubulars and the specimen of eight concrete-filled square CFRP-steel tubulars (CF–S-CFRP-ST) regarding compressive strength and a layer of CFRP [125]. Depending on the displacement curve of shear force, elastic stiffness and load-carrying capacity can be improved by increasing compression strength. Improving CFRP layers leads to a change in elastic stiffness and shear capacity. The experimental value is then evaluated using ABAQUS, and the formula for assessing the capacity of shear of CF-S-CFRP-ST is well correlated with the experimental value. Jahani et al. (2022) analysed and compared 23 RC beams of near-surface mounted (NSM) carbon FRP (CFRP) for the dependent based on time behaviour [126]. Temperature (20 and 50 °C), steel reinforcement ratio, and CFRP strengthening area are the factors considered for evaluation. Based on the deflections that show the temperature increase will not have any influence.

In contrast, the strengthening area has less effect on the deflections based on the dependence of time, which is identified experimentally depending on the age-adjusted effective modulus method (AEMM). Alkhawaldeh and Al-Rousan (2022) developed 12 Rc beams grouped under three forms of four joints at ambient temperature and temperature ranges of 400 °C and 600 °C [127]. Adding the CFRP layers one by one as one, two, and three are subjected to a quasi-static loading test. Structural performance depends on parameters such as stiffness degradation, energy dissipation, ductility of displacement, load of horizontal lateral displacement, and displacement ductility. After the experimental analysis, it has been proven that the presence of CFRP layers plays efficiently with the increase in heat damage at the RC beam-column joint, which leads to improved load capacity, increased lateral displacement, improved dissipation of energy, and delayed secant degradation of stiffness.

4. Emerging Materials in CFRP Composites

4.1. Nanostructured Carbon Fibres

Nanostructured CFRP carbon fibres are being studied for concrete reinforcement. Nanometer-diameter fibres have high tensile strength and modulus. CFRP-concrete composites may benefit from nanostructured carbon fibres. Yanming Li et al. (2019) investigated how nano-SiO_2/carbon fibre reinforcement affects oil well cement performance to improve its adaptability to oil well pressure. Compressive, tensile, modulus of elasticity, deflection, pull-out, and bridging effects improved [128]. Pitcha Jongvivatsakul et al. (2022) examined whether CNTs can improve concrete-CFRP bonding. Epoxy with 0.5% SWCNTs and 1.0% MWCNTs improved bonding strength, ultimate slip, effective bond length, bond stress-slip relationship, interfacial fracture energy, and crack formation [129]. Yuhang Du et al. (2022) studied the preparation, dispersion, change laws, and effect mechanisms of the dynamic compressive strength of modified carbon nanotube-fiber reinforcements (MCNF). Carbon nanotubes are easier to deposit on the negative electrode, and MCNF dispersion in an alkaline environment increases with polycarboxylate superplasticizer content. MCNF concrete had 14.0–35.5% higher dynamic compressive strength than untreated concrete, peaking at 0.3% MCNF content [130].

4.2. Hybrid Fiber Reinforcement

Hybridization creates high-performance composites by combining fibres. Hybrid fibre reinforcements such as carbon-glass or carbon-aramid are being investigated for CFRP-concrete applications. This approach uses complementary fibre properties to optimise composite performance. Rajai Al-Rousan et al. (2021) used the CFRP sheet to reinforce RC beams internally. The study assessed the CFRP sheet's flexural performance and efficiency as primary or supplemental flexural longitudinal steel reinforcement. Internal strengthening significantly improved most parameters [131]. Milad Abolfazli et al. (2023) assessed the bond strength of fibre-reinforced polymer (FRP) tubes and seawater sea sand concrete (SWSSC) following exposure to varying temperatures. The testing of 27 samples included glass FRP, carbon FRP, and hybrid glass-carbon FRP. The tubes with the strongest and weakest bond strengths were GFRP and CFRP, respectively, when exposed to elevated temperatures [132].

4.3. Self-Sensing CFRP

Self-sensing CFRP composites monitor strain and damage. Conductive fillers such as carbon nanotubes or graphene can give CFRP composites electrical conductivity. Measurements of electrical properties can detect structural damage or deformation in real-time. Using electrical insulation techniques, Sang-Hak Lee et al. (2020) propose and fabricate a CFRP-based shape memory alloy hybrid composite (SMAHC) beam with embedded shape memory alloy (SMA) actuators. Self-sensing-based deflection control was well controlled, but there was a slight delay in response time. Future research will concentrate on eliminating this delay [133]. Akira Todoroki et al. (2014) proposed a self-sensing time domain reflectometry (TDR) method for CFRP plates that uses a narrow-strip line to determine the transverse location of the damage. The findings apply to damage monitoring [134]. Pyeong-Su Shin et al. (2023) compared the self-sensing of CFRP and dual fibre composite (DFC) in a three-point bending test. The change in CFRP's electrical resistance (CER) trend was similar to that of dual fibre composite (DFC), but the interface between two fractured CFs had a greater impact. The interface between CFs in composite materials impacted the self-sensing of CFRP [135].

4.4. High-Modulus Carbon Fibres

Traditional CFRP materials use standard-modulus carbon fibres with 200–250 GPa tensile modulus. However, 300-GPa-plus high-modulus carbon fibres are being developed. High-modulus fibres stiffen concrete structures, improving load transfer. Isamu Yoshitake et al. (2020) investigated near-surface-mounted (NSM) strengthening for wheel-loaded cantilevered-reinforced concrete (RC) bridge deck slabs. Ultra-high-modulus (455 GPa) CFRP rods were used to strengthen bonds. Monotonic and cyclic loadings tested 15 RC beam (160 mm) specimens. The flexural fatigue test showed that the strengthened beams survived 2 million cycle loadings [136]. Nitin Lamba et al. (2023) investigated the mechanical properties of high-strength concrete with recycled CFRP fibres. The hardened properties of concrete test samples were determined using the Ultrasonic Pulse Velocity Test (UPVT) and compressive strength tests. Crystalline materials were characterised using X-ray diffraction analysis, while mechanical properties were evaluated using linear regression analysis [137].

5. Promoting Sustainability through Enhanced Structural Durability and Longevity

Incorporating CFRP composites into concrete promotes sustainability by increasing structural durability, decreasing energy demands, reinforcing existing structures, and decreasing cement consumption. These characteristics contribute to sustainable building practises and are consistent with efforts to fight climate change. Zhang et al. (2019) evaluated the mechanical performance and efficiency of epoxy-coated CFRP-reinforcement laminates in various configurations of recycled concrete beams. The outcomes demonstrated enhanced ductility, load-bearing capacity, fracture toughness, and fracture energy. Utilising digital image correlation (DIC), strain evolution and fracture propagation were captured. There is a need for pilot tests to increase confidence. High-quality recycling programmes should be implemented [138]. Chen Xiong et al. (2021) examine the viability of collaboratively using recycled CFRP fibre-reinforced rubberized concrete (RFRRC). The results of the experiments indicate an increase in compressive strength, ductility, flexural toughness, impact resistance, and energy absorption capacity. The ecological evaluation reveals a decrease in CO_2 emissions and an increase in mechanical properties [139]. Sebastian George Maxineasa et al. (2015) evaluate and compare the environmental performances of an unreinforced reinforced concrete (RC) beam with those of various CFRP flexural strengthening techniques using the Life Cycle Assessment (LCA) methodology. The results indicate that the environmental impact of all evaluated CFRP strengthening solutions is significantly less than that of the RC beam. The cement and steel reinforcement manufacturing phases have the greatest environmental impact. The paper concludes that the use of composite materials can contribute significantly to the sustainable development of the building industry [140].

According to Prathamesh Khorgade et al. (2022), CFRP is an excellent substitute for conventionally used steel in the construction industry. This study examined the environmental impact of two bridge systems, Rosensteinsteg II and a flyover over German highway A-20 and found that cradle-to-gate CO_2 emissions were reduced by 28% and 18% for conventional building materials and CFRP, respectively. This suggests that prestressed CFRP bridges are the most environmentally viable option, particularly for bridges that do not experience heavy vehicular loads [141]. Zhuo Tang et al. (2020) studied the compressive behaviour of geopolymeric recycled aggregate concrete (RAC) encased in CFRP jackets. Increasing the thickness of the CFRP jacket resulted in a significant increase in the compressive strength and ultimate strain of geopolymer concrete. Empirical stress and strain models have been recommended to predict the final condition of CFRP-confined geopolymeric concrete [142].

6. Disadvantages of CFRP Composites

Numerous benefits are associated with the use of CFRP composites in construction, but it is essential to consider the material's disadvantages. Poor transverse shear and weak fire resistance are two significant disadvantages of CFRP. Understanding these limitations is crucial to making informed decisions and designing CFRP structures effectively in the construction industry.

1. Their relatively low transverse shear resistance is one of the disadvantages of CFRP composites. It is well known that CFRP materials have a lower shear strength in

the transverse direction than their high tensile strength in the longitudinal direction. This restriction must be considered during structural design to ensure adequate reinforcement and load distribution;
2. CFRP composites are fire-prone. CFRP is strong at ambient temperatures but degrades at high temperatures. CFRP's organic resin matrix degrades easily in fires. Fireproofing CFRP structures requires coatings or encapsulation;
3. CFRP composites cannot redistribute loads such as steel or concrete. CFRP fails suddenly without warning or plastic deformation when it reaches its load capacity. This behaviour may require structural redundancy or progressive collapse prevention strategies;
4. CFRP costs more than steel and concrete. Carbon fibre production and resin impregnation increase costs. In cost-effective construction projects, this cost factor can affect CFRP adoption;
5. UV radiation can degrade CFRP composite resin matrices, reducing their mechanical properties. Over time, sunlight and outdoor conditions can discolour, delaminate, and reduce performance. For CFRP structures to last, UV protection measures such as coatings or UV-resistant additives must be taken.

7. Current Trends and Future Outlook for CFRP Composites in Civil Engineering

CFRP composites are rapidly gaining acceptance in the construction industry for strengthening and repairing concrete structural elements. Here are five current trends and future outlooks for CFRP composites in concrete structural elements:

1. Increasingly, CFRP composites are used in seismic retrofitting initiatives for existing buildings to improve earthquake resistance. This trend is anticipated to continue as more buildings are identified as vulnerable to seismic hazards;
2. Developing new manufacturing techniques for CFRP composites is anticipated to increase production efficiency and reduce costs. This could increase the use of CFRP composites in the construction industry;
3. Integration of CFRP composites with other building systems, such as Building Information Modelling (BIM) and other digital technologies, is on the rise. This can assist in optimising the design and construction process, decreasing waste, and enhancing project outcomes;
4. There is potential for using CFRP composites in new applications, including soil reinforcement, bridge construction, and other infrastructure projects. CFRP composites are already used in a variety of concrete structural elements;
5. The construction industry is increasingly concerned with sustainability, and CFRP composites are viewed as a more sustainable alternative to conventional building materials. As more building owners and developers prioritise sustainable design and construction, the demand for CFRP composites will increase;
6. CFRP is a unique material that demonstrates minimal changes in its mechanical properties under varying temperature conditions, making it suitable for structures exposed to high temperatures or rapid temperature fluctuations. This characteristic enables the use of CFRP in applications including aerospace components, industrial buildings, and high-temperature storage facilities;
7. Highly resistant to corrosion, CFRP composites are ideal for marine environments. They do not corrode or deteriorate in saltwater, ensuring long-lasting durability and dependable performance in mooring systems. In addition, they have high fatigue resistance, allowing them to withstand cyclic loading and stress cycles, thereby reducing the risk of material fatigue and extending the service life of mooring systems. This makes CFRP a dependable material for maintaining the stability and safety of marine structures and vessels.

8. Conclusions

CFRP has emerged as a high-performance composite material with numerous advantages in the construction industry. Its exceptional properties, which include a high modulus of elasticity, superior strength-to-weight ratio, fatigue strength, and tensile strength compared to other FRP composites, make it highly desirable for various structural applications.

The ductility and flexural strength of concrete columns, beams, and slabs can be substantially improved by employing CFRP as external reinforcement and lamination. In addition to reducing reliance on conventional reinforcement, this method mitigates premature failure due to corrosion or degradation. Additionally, CFRP's exceptional fire and chemical resistance increases its suitability for harsh environments.

Despite obstacles such as the relatively high cost and the need for specialised installation techniques, the advantages of CFRP in construction make it an attractive material for the industry's future. Its use can potentially improve structures' safety, durability, and sustainability, thereby promoting resilience in the face of climate change and other environmental factors.

As manufacturing processes continue to advance and CFRP becomes more accessible, the construction industry is anticipated to emphasise the development and adoption of CFRP for structural applications. This trend will permit the development of resilient and sustainable structures to withstand future challenges. With continued research and innovation, CFRP has the potential to revolutionise the construction industry and make it more resilient.

Author Contributions: Conceptualization, D.S.V., P.D. and A.S. (Arvindan Sivasuriyan); methodology, E.K. and A.S. (Anna Stefańska); validation, A.S. (Arvindan Sivasuriyan) and E.K.; investigation, D.S.V., P.D. and Ł.W.; resources, D.S.V., P.D., Ł.W. and A.S. (Anna Stefańska); data curation, A.S. (Arvindan Sivasuriyan) and A.S. (Anna Stefańska); writing—original draft preparation, D.S.V., P.D., A.S. (Arvindan Sivasuriyan), A.S. (Anna Stefańska), E.K. and Ł.W.; writing—review and editing, A.S. (Arvindan Sivasuriyan) and A.S. (Anna Stefańska); visualization, D.S.V., P.D. and A.S. (Arvindan Sivasuriyan); supervision, A.S. (Arvindan Sivasuriyan) and E.K.; project administration, A.S. (Arvindan Sivasuriyan), A.S. (Anna Stefańska) and E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available upon request from the corresponding authors and shared after his consideration.

Conflicts of Interest: The authors declare no conflict of interest.

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