

Review

Fiber-reinforced polymer (FRP) in concrete: A comprehensive survey

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ABSTRACT

This work focuses on how different aspects of design, testing, and field implementation of fiber-reinforced polymer (FRP) in concrete have gained attention from the scientific research community. FRP composites have gained significant recognition after being implemented in civil engineering applications over the past three decades. This paper conducts a comprehensive survey of the existing literature on FRP in concrete from different engineering aspects. Since its advent, FRP research has resulted in numerous peer-reviewed papers available in various scientific databases such as Elsevier, ASCE, Springer Nature, ACI, and MDPI. Researchers investigated the use of FRP in concrete from different aspects, including material systems, element types, and applications, accounting for 35.8%, 50.3%, and 13.9% of the research publications, respectively. This paper aims to present an overview and summarize the use of FRP based on highly cited literature and to support FRP's continued growth and development in concrete applications. Consequently, this paper is expected to offer advantages to stakeholders involved with FRP use, such as owners, engineers, and professionals, by emphasizing the number of available research publications, which can increase confidence in adopting FRP. It offers scholars and researchers the opportunity to become acquainted with the use of FRP in the application of concrete.

1. Introduction

Concrete is well-known for its resiliency and compressive strength and is the second most used manufactured material globally. Concrete has been a vital component in the development of civilization, serving as the key material for a wide variety of construction, including buildings, bridges, and many other types of engineered and non-engineered applications. As such, there is a continuous need to enhance the service life of concrete structures and make them more durable, sustainable, and resilient to support society's needs.

The combination of nonmetallic materials such as FRP and concrete carries a plethora of advantages. For example, FRP reinforcement has a higher strength-to-weight ratio than steel; it is possible to reduce the total weight of structures without compromising their structural soundness by using FRP. It can accelerate the installation and building process. Additionally, since it does not corrode, it can tackle durability issues related to the corrosion of steel reinforcement in concrete. This results in improved endurance, lower maintenance costs, and a longer lifespan for concrete structures. Moreover, its electromagnetic transparency and the fact that it does not carry electricity make some types of FRP ideal for specific applications such as Magnetic Resonance Imaging

(MRI) rooms [1]. Moreover, using FRP composites in concrete construction allows for a more significant degree of design flexibility. Because of these benefits, the combination of FRP with concrete has been recognized and implemented in civil engineering, as demonstrated by the publication of international design guidelines and codes.

Nevertheless, engineers and researchers continue to investigate and develop the usage of FRP in various concrete applications to address knowledge gaps. This paper explores the use of FRP in the civil engineering field across multiple sectors. Fig. 1 shows the classification of FRP in concrete, which is based on material systems, types of elements, and applications.

This paper provides the following:

- A comprehensive survey of FRP applied to concrete from a view of material systems, element types, and applications.
- A statistical analysis of the classified peer-reviewed publications in various scientific databases.
- A review of the research pinpointing knowledge deficiencies and those with a higher degree of focus and significance on the topic.
- The potential future path for research and development in FRP.

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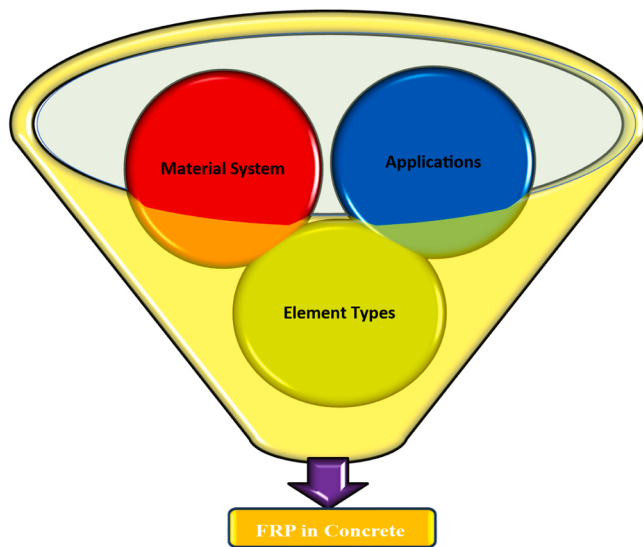


Fig. 1. Classification of FRP in concrete.

The survey aims to answer several questions. Firstly, it identifies which publishers issue the most FRP-related papers. Secondly, it aims to analyze historical trends in the publication of FRP-related papers. Additionally, the survey aims to determine the countries that contribute the most to FRP publications & also identifies the most popular topics within the field. Furthermore, the survey examines the publication trend in recent years and explores how external events have influenced these publishing trends. Moreover, the survey analyzes which topics have received the most attention. Finally, it identifies the areas that require more attention in FRP research.

The overall layout of this paper is structured as follows: [Section 2](#) presents the background of FRP. [Section 3](#) divides the 'FRP in concrete' into material systems, element types, and applications. [Section 4](#) discusses the findings, while [Section 5](#) provides the derived conclusions and potential avenues for future research.

2. Background of FRP materials

FRP composite materials comprise three major components: fibers, polymers, and various additives and fillers. In FRP composites, continuous fibers with high strength and stiffness are impregnated using a polymeric matrix with a relatively lower modulus and higher ultimate strain than the fiber. The direction in which the fibers run is determined by the stress applied to the composite element since fibers are the load-carrying component. At the same time, the resin distributes the load and protects the fibers. The variety of additives may include plasticizers, flame retardants, blowing agents, coupling agents, and various combinations. In addition, it is possible to trace the presence of coatings, pigments, and fillers [2]. Understanding the characteristics and behavior of the composite material's constituent parts is essential to make the most of the potential composites in structural applications.

Due to their molecular alignment along the fiber direction as well as the lower defect frequency in comparison to the bulk material, FRP composites are considerably more robust than the bulk material from which they are derived. The fibers that are used in composites typically possess the following characteristics: a high elastic modulus, a high ultimate strength, minimal strength variation between individual fibers, stability of properties during handling and fabrication, consistency in fiber diameter and surface, a high level of toughness and durability, availability in suitable geometries and forms, and an affordable cost.

The advancements made during World War II, notably in the fabrication of the first radomes to handle electronic radar equipment, motivated using FRP in the construction and building industries after the war

ended. According to Hollaway [3], the 1960 s experienced the beginning of significant curiosity in using glass fiber/polyester composites in building and scientific advancements in this area. Both a dome structure in Benghazi (1968) and a roofing structure at the Dubai airport (1972) were constructed using Glass FRP (GFRP) during this time. Both structures are notable projects. Fiber and FRP manufacturers began focusing on cost reduction in the late 1980 s and early 1990 s as the defense market decreased [4]. This was done to secure the FRP manufacturing industry's ability to continue growing over time. Since the early 1990 s, there has been a steady rise in the need for infrastructure maintenance and renewal, which has led to a growth in the usage of FRP materials in structural applications. To this end, FRP has become more cost-effective. To date, hundreds of practical applications of FRP may be found in structures worldwide. The Ibach bridge in Lucerne, Switzerland, was the world's first CFRP concrete reinforcement bridge, restored in 1991 using three CFRP strips. This achievement gives the Ibach Bridge a place of distinction. Some other sources may be consulted for more extensive historical views and reports on worldwide development [5–8].

For 25 years, scientists have looked at various FRP-based approaches to resolve plain and reinforced concrete (RC) issues. In this study, articles related to FRP in concrete have been collected. The total number of published FRP manuscripts relevant to RC is presented in [Fig. 2](#), which shows a wide variety of periodicals. Based on this analysis, Elsevier published 36% of these manuscripts. In comparison, ASCE contributed 13.4%, Springer contributed 6.7%, MDPI contributed 4.1%, ACI contributed 3.8%, Taylor and Francis contributed 3.5%, Trans Tech Publications Ltd 3.4%, SAGE contributed 2.6%, Techno-Press contributed 2.4%, and other outlets contributed 24%. [Fig. 2](#) also demonstrates that Elsevier published the most FRP in concrete-related papers.

[Fig. 3](#) presents a bar chart illustrating the number of FRP-related publications on an annual basis from 1997 to 2022. The number of publications rose steadily from 29 to 701.

An exhaustive search through all reputable databases was conducted, and relevant papers were compiled based on the titles, keywords, and abstracts. After the initial investigation, each paper underwent a thorough examination, during which both the topic and category utilized were considered to clarify the manuscript. During the screening process, duplicate items were removed. Finally, the articles associated with the FRP in concrete were grouped. [Fig. 4](#) provides a flowchart of the stages of the research process. FRP is not exclusively a subject of interest in structural engineering; its relevance extends to numerous other disciplines, such as computer science, material science, mechanics, and more, as evidenced by the research papers published in these areas.

[Fig. 5](#) provides the quantity of FRP-related work in different fields, such as material science, construction, and building technology. Additionally, there is a considerable opportunity in the field of computer science, focusing on predicting the behavior of FRP under various conditions and experiments.

[Fig. 6](#) shows that China and the USA are pioneers in FRP-related research by publishing 1976 and 1448 papers, respectively. This higher number of publications can be attributed to the well-developed economies of these two countries, which allows them to provide more funding for research and development in this field. In addition, the increasing concerns related to repairing deteriorated infrastructures and the interest in finding a solution for future construction to avoid unnecessary repair and maintenance costs in the US is another significant driving force in the development of FRP. Countries such as Canada, Australia, Italy, and Iran also contribute considerably to FRP-concrete research. This global interest indicates the importance of FRP across different countries, fostering international collaboration on projects in this field of study.

3. Classification of FRP in concrete

Three distinct categories were developed herein to conduct the comprehensive literature review survey of FRP in concrete. These

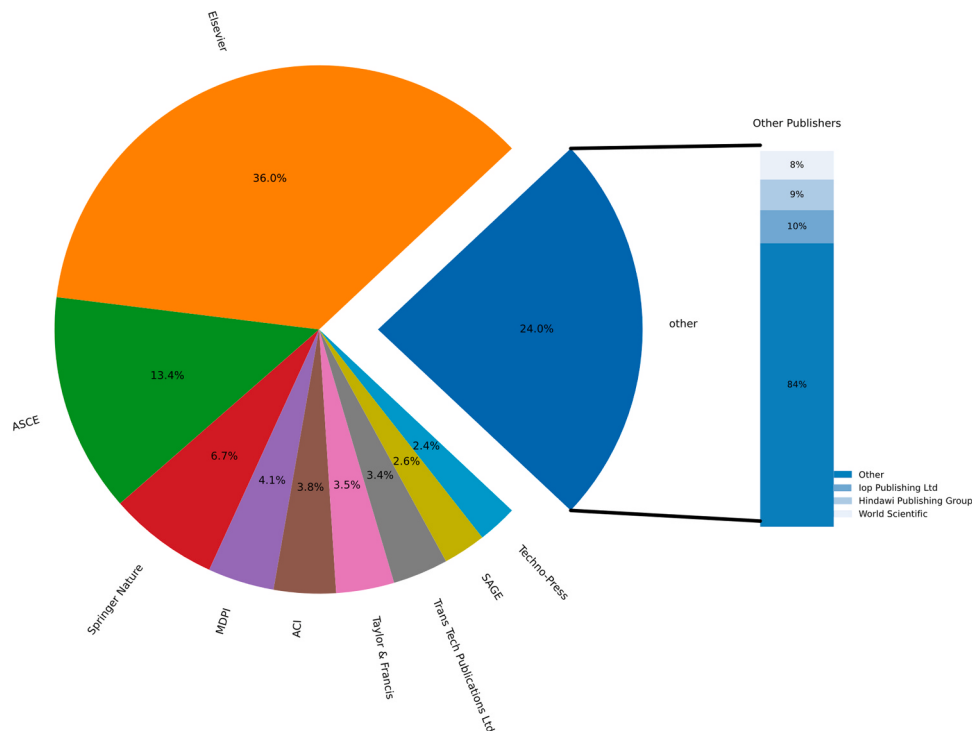


Fig. 2. Percentage of FRP in concrete-related papers across various publications.

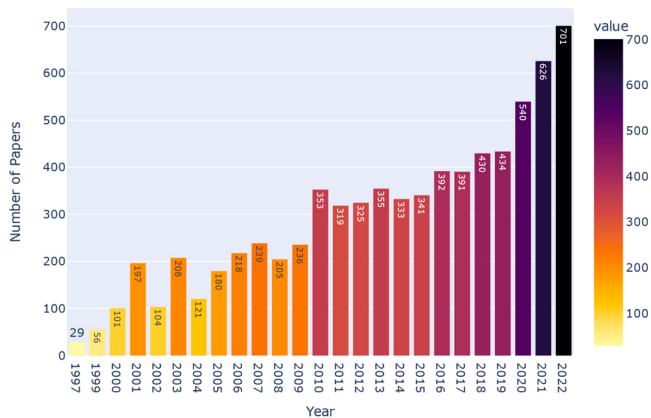


Fig. 3. Number of FRP and concrete-related publications from 1997 to 2022.

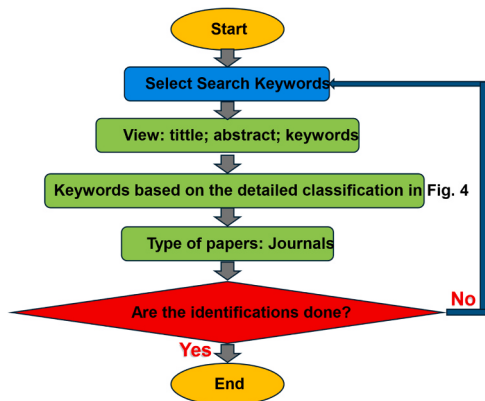


Fig. 4. Flowchart of reviewing process.

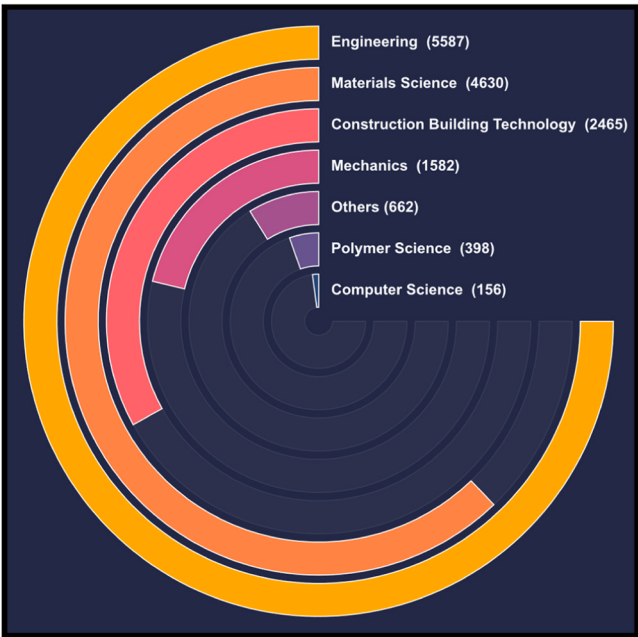


Fig. 5. Number of papers in different FRP-related fields.

classifications were further divided into subcategories to enable more detailed analysis based on highly cited published papers. It should be observed that the sequence of related research in each subsection is organized according to the importance of the studies.

The comprehensive review ensures a thorough understanding of the subject, bringing together a broad range of resources to create a concrete picture of the current state of research related to FRP. Fig. 7 presents the mind map categorization of FRP in concrete. The classification in this figure is based on material systems, types of elements, and applications. To simplify the complexity of the literature analysis and provide a more

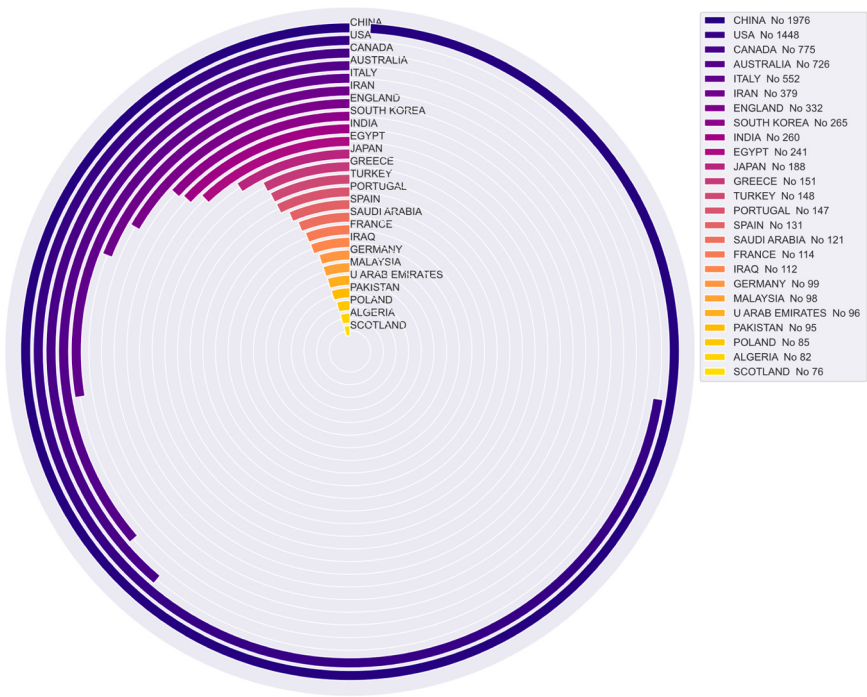


Fig. 6. Comparison of countries in terms of the number of papers in FRP.

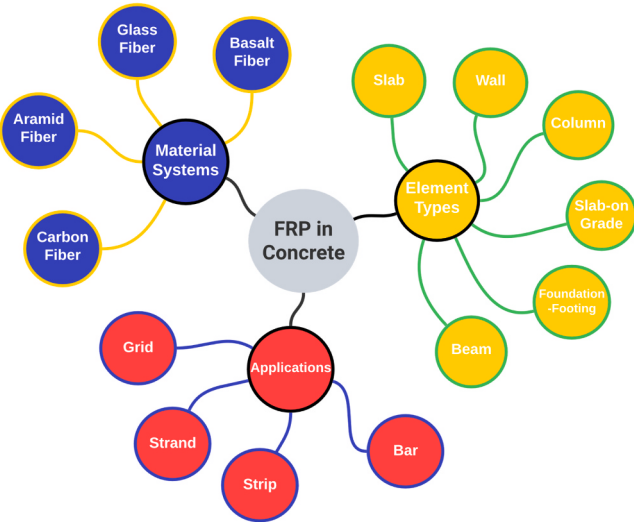


Fig. 7. Detailed classification of FRP in concrete.

thorough investigation of a limited area, the authors narrowed down the material system category to the only subcategory of fiber types.

3.1. Material systems

Glass, basalt, carbon, and aramid fibers are primary materials utilized for the manufacturing of FRP composites, and each of them has its own specific physical and mechanical behavior [9,10]. The fibers are load-carrying components of FRP, and their characteristics have a critical impact on the mechanical behavior of the final product [11]. When classifying FRP within material systems focusing on fiber type, four categories can be established: GFRP, Carbon FRP (CFRP), Basalt FRP (BFRP), and Aramid FRP (AFRP). According to Fig. 8, CFRP is leading with 58.21% and is identified as the most widely researched. GFRP secured the second position and accounted for 32.49% of the papers.

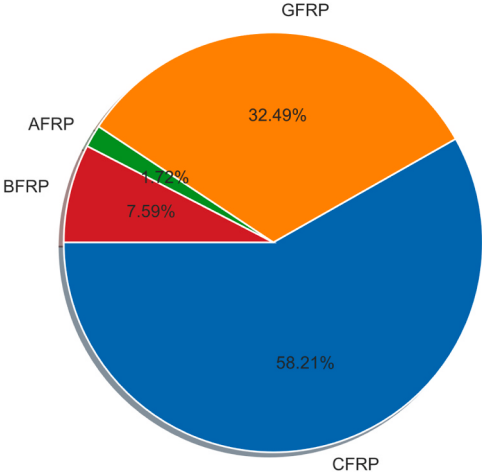


Fig. 8. Percentage of GFRP, CFRP, BFRP, and AFRP in the FRP-related publications.

BFRP and AFRP lag with 7.59% and 1.72%, respectively, indicating that these materials have been less extensively explored within the context of FRP in concrete. The subject of CFRP is currently trending in research, whereas BFRP and AFRP have been identified as requiring further exploration and development. These clearly illustrate the current focus and potential future direction of research in the area of FRP in concrete.

According to Fig. 9, a dramatic increase was seen in the number of papers published from 2018 to 2022. This heightened level of research activity was reflected in the papers on CFRP and GFRP, with the tally reaching 487 and 350, respectively.

A significant surge in publications related to BFRP was witnessed from 2018 to 2022 as the count escalated from 35 to 128 (See Fig. 9), indicating the potential to become a major research area in the future. This growing interest in BFRP-related research can be attributed to the increasing supply of basalt fibers in the US since 2018 [12], making

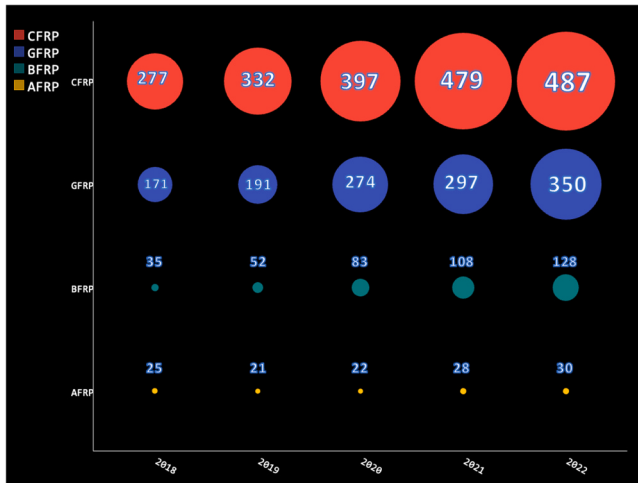


Fig. 9. Number of published papers for CFRP, GFRP, BFRP, and AFRP from 2018 to 2022.

manufacturing more cost-effective. However, in the case of AFRP, the number of published papers remained relatively stagnant over the same time frame.

3.1.1. Glass fiber

The most frequently used fiber in the fabrication of FRP is glass fiber due to its lower price. Depending on the percentage of materials utilized in the manufacturing of glass fibers, there are various types of glass fibers with specific mechanical behavior [13]. Fig. 10 shows different types of glass fibers and their unique properties.

Y. Fu et al. [14] evaluated the effects of short fibers in polypropylene composites. The samples were prepared using extrusion compounding and injection molding processes. Moreover, two fiber efficiency factors were used to interpret the composite strength and modulus. Results showed that fiber volume decreases the fiber efficiency factor. In addition, regarding the fiber efficiency factor, this number was much higher for composite modulus than for composite strength.

Ou et al. [15] assessed the impact of different strain rate levels with various temperatures between -25°C to 100°C quasi-static loading. Results of tested samples demonstrated that raising strain rates at room temperature improves tensile strength, maximum strain, and toughness. However, at the strain rate of 40 s^{-1} , increasing the temperature causes a reduction in tensile strength, toughness, and Young's modulus.

Moreover, Weibull statics was adopted to assess the degree of Changes in tensile strength. Obtain Weibull parameters that apply to numerical simulations and engineering applications.

The effects of different environmental factors on the tensile properties of glass fiber were explored by Agarwal et al. [16] Results indicated that environmental conditions have an adverse effect on the tensile strength of glass fibers.

Zaghloou; et al. [17] prepared three different sample sets, namely Unreinforced (UR) polyester, surface-reinforced arranged (SRA) composites, and bulk-reinforced arranged (BRA) to evaluate the effects of fibers arrangements on tensile and fatigue behavior of glass fiber-reinforced polyester. A scanning electron microscope, a rotating bending fatigue machine, and a universal testing machine were employed to analyze the performance of samples under fatigue and tensile stresses. Results showed that SRA accounts for the largest life span compared to the other two samples.

Mukhopadhyaya et al. [18] cast 24 specimens to explore the effect of aggressive conditions on the behavior of concrete joints strengthened with GFRP. Specimens with two different compressive strengths were exposed to accelerated aging environments for nine months. Results showed that all environmental regimes increased bond transfer length, the magnitude of shear stress distribution, and plate slip. It should be noted that exposure time was not adequate to investigate the effect of accelerated environments on the strength of the joints.

Habeeb et al. [19] conducted experiments to assess the effect of the amount of reinforcement on the flexural performance of continuous beams reinforced with GFRP bars. Results showed that over-reinforcing continuous or supported beams plays a significant role in crack width. Moreover, over-reinforcing is a key component in crack propagation and enhancing the load capacity of the beam. In addition, over-reinforcing continuous and supported beams reduce their deflection.

Robert et al. [20] examined how the bonding strength between GFRP bars and concrete is affected by aging conditions. The researchers inserted GFRP bars into concrete and subjected them to tap water at various temperatures to expedite degradation. The results suggest that the durability of GFRP bars in concrete is insignificantly affected by aging conditions.

Mahmoud et al. [21] conducted a study where they utilized eight rectangular concrete columns reinforced with GFRP bars to examine how these columns perform under seismic loads. The specimens were subjected to a combination of constant lateral load and cyclic quasi-static load during testing. Results revealed that the drift capacity of the tested specimens at failure was 8.5–12.5%. Dissipated seismic energy also shows that GFRP-RC columns can be used instead of steel-RC

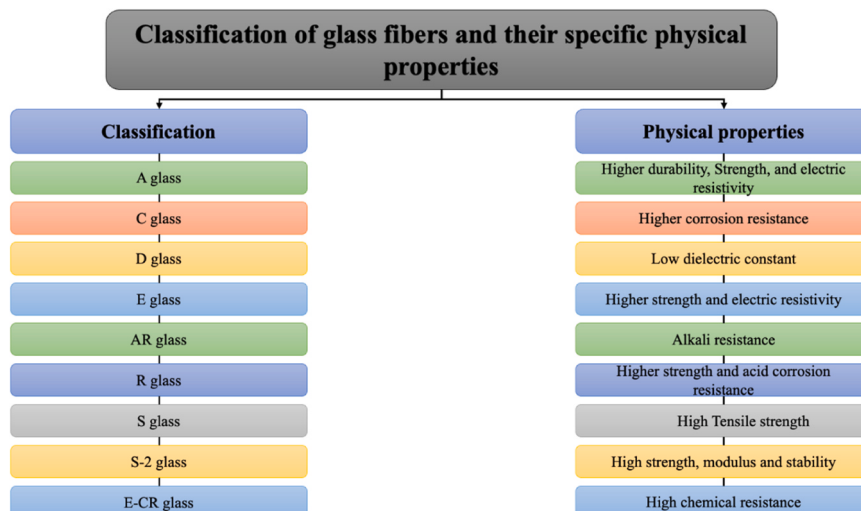


Fig. 10. Different types of glass fibers.

columns for a constant lateral load.

Kumutha et al. [22] conducted a study to investigate the impact of GFRP wrap on the axial response of rectangular columns. Nine specimens were provided and subjected to axial force up to failure. Results revealed that the more layers used for strengthening, the more load-bearing capacity columns will have. Moreover, using GFRP wrap as a strengthening method for concrete columns makes a valuable contribution to their compressive strength.

Qu et al. [23] cast eight concrete beams reinforced with hybrid GFRP and steel bars to investigate the effects of reinforcement ratio and the ratio of the FRP bars to steel bars on the flexural performance of casted hybrid reinforced beams. According to the results of the experiments, normal reinforcement-ratio beams experienced acceptable ductility, serviceability, and load capacity. Moreover, the proposed analytical method offered acceptable agreement with experimental results.

3.1.2. Carbon fiber

Carbon fibers have a wide range of applications in industry. Fabrication of tool parts, medical tools, rotary blades, helicopters, engine parts, satellites, and rehabilitation and reinforcing materials in construction are vivid examples of the application of this fiber in engineering practices. Even though, the fiber cost is an obstacle [24] their exceptional characteristics such as less vulnerability to creep rupture, resistance to alkaline and acidic solutions, and ability to tolerate higher sustained stresses make them appropriate material in different applications such as prestressing [25,26].

Thermally activated weakening in carbon-epoxy laminates is the softening mechanism causing the failure event in this material during the fire. Feih et al. [27] evaluated the tensile strength and identified a softening mechanism on T700 carbon fiber experimentally. Results showed that increasing temperature (above 500 °C) decreases the fiber modulus. Corrosion of the higher stiffness layer in the near-surface fiber area is the reason for this reduction. It should be noted that heating fiber without surface oxidation does not affect fiber modulus. This reveals that oxygen content is the active factor in the loss of stiffness in carbon fiber exposed to fire. Unlike the modulus of fiber, the tensile strength of fiber has nothing to do with the existence of the oxygen content. Results showed that the tensile strength of the carbon fiber decreases by up to 50% when exposed to a temperature between 400 and 700 °C.

Tensile and flexural creep tests were used by Goertzen et al. [28] to investigate the creep behavior of carbon fiber composites. According to the findings, there is no creep rupture failure when carbon fiber reinforced composites are subjected to tensile creep loads of up to 77% of their ultimate tensile strength in a short duration and at room temperature. Moreover, using constant activation energy assumption to obtain the shift factor for the carbon fiber reinforced composite is acceptable only for the samples that experienced temperature under glass transition temperature (T_g).

Cao et al. [29] proposed a method to predict temperature-dependent tensile strength of unidirectional CFRP composites by using numerical analysis and model simulation, and results were compared with experimental values. Glass transition of the matrix, glass transition region, and residual tensile strength after the glass transition region were the model's parameters. Results indicated tensile strength of CFRP sheets remains stable at the low temperature below T_g . However, tensile strength plummets during T_g , and then it remains constant. Moreover, the suggested model for predicting the tensile strength of CFRP versus different temperatures shows a good agreement compared to experimental results.

Xia et al. [30] evaluated effects of strain rate on tensile behavior of carbon fiber-reinforced aluminum. The strain rate range was adopted between 0.001 s^{-1} to 1200 s^{-1} . Results indicated that this material's tensile strength and failure strain increase with the increase in the strain rate. Moreover, a linear strain hardening model and Weibull distribution were adopted to obtain a constitutive equation for this material. Analysis showed that the Weibull scale parameter is sensitive to the strain

rate and raises with increasing strain rate.

Carbon fibers have a wide range of industrial applications. Fabrication of tool parts, medical tools, rotary blades for helicopters, engine parts, satellites, and rehabilitation and reinforcement materials in construction are vivid examples of this material's application in engineering practices. However, fabrication cost is an obstacle to the widespread use of this type of fiber [31].

Zhou et al. [32] explored the impacts of the ply thickness between 0.02 mm to 0.1 mm on tensile properties and fracture behavior of the carbon fiber-reinforced laminates experimentally and theoretically. Four laminates were prepared using the novel technique of combining airflow with mechanical spreading. This technique helps to explore the influence of the thinning technique in the ply on fiber alignments and, as a result, on the tensile and fracture properties of the laminates. The suggested mechanical property prediction model for carbon fiber reinforced laminate performed well compared to the experimental results.

Lee et al. [33] assessed the effects of elevated temperatures (150, 250, 350, and 450) on the microstructure and microhardness features of CFRP. Crystal structural features of the epoxy resin and carbon fibers used for the fabrication of the CFRP were explored to investigate the microstructures of the samples under the mentioned temperature. Results showed that elevated temperatures cause a reduction in the hardness of CFRP and mechanical degradation of resin, fiber/matrix debonding, and extending the micro-cracks on the surface of samples are reasons for this reduction.

Rafi et al. [34] cast four concrete beams reinforced with CFRP bars to evaluate the bending performance of CFRP-RC beams in flexure. A model was proposed to predict the bending performance of tested specimens. Results revealed that the failure mode was in agreement with the predicted model. Furthermore, CFRP-RC beams showed ductile failure because the deformability factor for such beams was higher than 6, and beams had no deflection issues. This is due to the high elastic modulus of CFRP bars compared to other FRP bars.

An experimental investigation on the bond performance of FRP bars in ultra-high performance fiber reinforced concrete (UHPFRC) was undertaken by Firas et al. [35] due to the significance of the bond behavior of CFRP bars in prestressed components. The bond performance of CFRP bars with different surface treatments, namely smooth and sand-coated surfaces, was tested in a pull-out test setup. Results indicated that the bond strength of CFRP bars with varying treatments of the surface had negligible differences. In addition, the diameter of the bar and the embedment length negatively influenced the bond strength of the bars.

The effects of Near-Surface-Mounted (NSM) CFRP bars in strengthening T-beams in shear were investigated by Rahal et al. [36]. The impact of bar orientation and type (steel and CFRP) were studied, and results revealed that this strengthening method could increase the shear capacity of concrete T-beams by 37–92% compared to the control specimen. Additionally, the results revealed that placing bars at 45° is the optimal orientation for strengthening such beams with steel or fiber-reinforced polymer materials in shear. Moreover, the shear capacity of the specimens reinforced with CFRP bars was 10% larger than steel ones. The bond strength of CFRP and GFRP bars in high-strength concrete was identified as a topic worthy of study by Davalos et al. [37]. CFRP bars were exposed to two different environmental conditions, including tap water with an ambient temperature of 60 °C and varying temperatures between –20 °C and 60 °C. The results of 48 pull-out tests indicated that environmental condition has an adverse effect on the bond strength of CFRP by up to 4–10%. As for the GFRP bars, this reduction was in the range of 0–20%.

Barnes et al. [38] provided three RC beams externally strengthened by CFRP plates to investigate how this material affects the fatigue performance of the beams. All specimens were tested under three different loading conditions, which included applying equivalent loads in strengthened and unstrengthened specimens, applying loads to both beams in such a way as to apply the same stress in rebar, and applying the same portion of ultimate capacity to every tested beam. Results

showed that failure of internal steel reinforcement in tested beams governs the dominant failure.

Bukhari et al. [39] fabricated seven continuous concrete beams over two spans to assess the effect of the area and location of CFRP sheets within the span on shear strengthening. A total of fifteen beams were cast, including four reference beams and eleven beams reinforced with externally bonded CFRP sheets with different configurations. According to the results, the application of CFRP sheets proved beneficial in enhancing the shear strength of the concrete beams. Furthermore, it was suggested that aligning CFRP sheets at a 45-degree angle to the beam's axis is advantageous.

3.1.3. Basalt fiber

Basalt fiber is obtained from melted basalt rocks. In contrast to the production of glass fibers, which require a secondary raw component, Basalt fiber does not need another raw component [40]. In addition, due to their acceptable mechanical behavior and affordable price, the use of BFRP materials has been increasing in construction practices. This field has been the subject of considerable research.

Wang et al. [41] carried out an experiment to investigate the chemical durability and mechanical properties of alkali-proof basalt fiber fabricated by F46 epoxy resin. The approach of this study was in a way that, at first, Fibers were immersed and boiled in distilled water, sodium hydroxide, and hydrochloric acid before mass loss and fiber strength were determined. The results showed the basalt fiber's alkali resistance outperformed its acid resistance.

Greco et al. [42] studied the adhesion of the basalt fibers to polypropylene (PP) matrices. A single filament tensile test was used to determine the strength of different types of fibers from different sources with varying surface treatments. Furthermore, the critical length of the fibers was determined in a homopolymer PP matrix and a maleic anhydride-modified PP matrix, a single fiber fragmentation test was adopted. Studies showed that the origin or surface treatment has an infinitesimal effect on the tensile strength of the fibers. Moreover, fibers with any sizing account for reduced mechanical properties compared to other fibers. In addition, results indicated that the tensile strength of the fibers depends on the filament length.

Effects of dynamic load on tensile strength, tensile modulus, and failure strain at various strain rates, of basalt fiber were assessed by Chen et al. [43]. It was found that the mentioned tensile properties of basalt fiber surge when the strain rate is over 120 s^{-1} . Moreover, it was observed that the dynamic tensile strength of basalt fibers is about double of the quasi-static one.

Basalt fiber is a natural mineral fiber. Unlike natural fibers which are highly vulnerable to thermal and hygroscopic stress, basalt fibers have acceptable mechanical behavior in such conditions. Basalt fiber is obtained from melted basalt rocks. Compared to the production of glass fibers requiring a secondary raw component, this fiber does not need another raw component for its production [44].

Fegade et al. [45] reviewed of the chemical constituents, mechanical properties, and durability of basalt fiber reinforced composite, along with the cost of the basalt fibers compared with carbon and glass fibers. It was found that basalt fiber is better than carbon fiber in cost-effectiveness. Moreover, the strength of the basalt fibers should be considered. They perform better compared to glass fiber. It is worth mentioning that findings revealed that basalt fiber performs better in flexural strength and better adhesion compared to carbon and glass fibers. However, reducing the thermal properties of basalt fibers when subjected to high temperatures is one of the negative aspects of this fiber.

Plappert et al. [46] investigated the quasi-static mechanical characterization of the unidirectional basalt fiber/epoxy composite, including tension, compression, and shear. Outcomes revealed that, considering strength and stiffness, unidirectional basalt fibers perform the same or better than unidirectional glass fiber/epoxy composite. Moreover, when it comes to the production cost of these materials,

basalt fiber composites account for low manufacturing cost. It should be noted that basalt fiber composites have good recycling properties. These reasons lead to using basalt fiber composites in many engineering practices.

The flexural performance of concrete beams reinforced with a combination of BFRP, and steel bars was investigated by Ge et al. [47] The bond performance and tensile strength of the BFRP bars were evaluated using flexural testing on the concrete beams, pull-out tests, and tensile tests. The findings indicated that the bonding capacity between BFRP bars and concrete was comparable to that of steel bars. The formula proposed by the researchers to estimate the flexural performance of hybrid RC beams was accurate when compared to the experimental data.

Mahroug et al. [48] carried out a study on four continuous and two simply supported RC slabs reinforced with BFRP bars positioned at the top, bottom, or both. The goal of their research was to develop a code model. Results showed that continuous BFRP-RC slabs experienced the most significant deflection and wider crack width. Additionally, the concrete slab with BFRP reinforcement positioned both on the top and bottom exhibited the greatest load-bearing capability and the least amount of deflection when compared to alternative arrangements.

The effect of basalt fiber on the flexural performance of 12 concrete beams was studied by Abed et al. [49]. Concrete beams were reinforced with either GFRP bars or steel bars, and their bending performance was compared to the experimental results. Results indicated that using basalt fibers in concrete increases the tested beams' curvature ductility and flexural capacity. Enhancing the flexural capacity of concrete beams is rooted in the ability to delay the occurrence of concrete failure strain.

Hassan et al. [50] used direct tensile loading and pullout tests on BFRP bars after exposing them to an alkaline solution for six months to investigate their durability performance in harsh environmental conditions. Results showed that conditioned specimens at temperatures of 50°C and 60°C experienced an increase of 35–60% in their bond strength within their first 1.5 months of exposure. In contrast, there was a constant bond strength for the conditioned FRP bars at 40°C in the first 1.5 months of exposure time. Moreover, conditioned FRP bars at 40°C accounted for the highest reduction in bond strength after 6 months of exposure.

Thirty-six BFRP-RC cylinders and twelve GFRP-RC cylinders were evaluated by El Refai et al. [51] to study the bond performance of FRP bars. The bond-slip curves of BFRP and GFRP bars were determined to be statistically similar. However, the study revealed that the bond strength of BFRP is only 75% of that of GFRP bars.

3.1.4. Aramid fiber

Due to their outstanding structural characteristics, Aramid fibers have attracted much interest, and as a result, many studies have been conducted. While promising, the aramid fiber's smooth and chemically impervious surface significantly restricts its applicability to date. Various techniques have been employed to modify the surface of aramid fibers to enhance the interfacial adhesion between the fiber and the matrix material. To promote appropriate chemical bonding and mechanical interlocking, these surface modifications are made to boost chemical reactivity and roughness [52–54].

The dynamic viscoelastic properties of Kevlar 49 fibers were assessed by Raja et al. [55] through the implementation of an innovative continuous dynamic analysis (CDA) technique. This evaluation involved monitoring the storage modulus and loss factor of the fibers. Additionally, a correlation between the dynamic viscoelastic properties of Kevlar 49 and the structural data obtained from synchrotron radiation analysis using Raman scattering frequencies was established. The study's findings demonstrated that the storage modulus of Kevlar 49 is equivalent to its Young's modulus.

Youakim et al. [56] proposed a method to determine the prestress loss in AFRP strands by satisfying the requirements of equilibrium, compatibility and avoiding using any empirical multipliers. Results showed more prestress loss in steel strands than in FRP ones. It was

mentioned that the lower stress loss has a root in the lower modulus of elasticity in FRP strands. Moreover, the type of FRP strand and the initial stress distribution of each specific cross-section can significantly impact the extent to which the concrete stresses and deflection can vary from those of similarly prestressed steel strand girders over the long term.

The applicability of AFRP sheet to strengthen concrete columns was investigated by Toutanji et al. [57], and the obtained results were compared with unconfined concrete column specimens. Results indicated that using AFRP sheets to strengthen concrete columns significantly improves strength and ductility. Moreover, a method for the prediction of stress-strain response was provided. When comparing the proposed model with results from experiments, it was clear that the proposed method resulted in acceptable predictions. Following this research, Wu et al. [58] investigated using continuous and discontinuous aramid fibers as an external wrapping for concrete columns with high compressive strength. Like Toutanji et al.'s [57] research, an analytical model was offered to predict stress-strain curves for the specimens. When considering the strength of the specimens, the results aligned with Toutanji's research. However, in terms of ductility, using a discontinuous AFRP sheet cannot increase the ductility of the wrapped specimens significantly.

Ten beams reinforced with AFRP and steel bars were evaluated in a study by Rashid et al. [59] to compare the two materials' performance in a three-point bending test. Results showed that specimens reinforced with AFRP bars perform better in terms of flexibility during the post-cracking period than steel-RC beams and the dominant failure of the beam is flexure-shear failure mode.

There is much research on small-scale concrete columns reinforced with AFRP sheets and a limited number of studies have been conducted to investigate the effects of size on the axial performance of concrete columns reinforced with AFRP sheets. Extensive research has been done by Wang et al. [60] to assess the performance of the size effect of the columns reinforced with AFRP sheets. 99 short concrete square and circular columns with three different scaling dimensions were tested. Results indicated that the size effect significantly impacts the strength of columns reinforced with aramid sheets. As opposed to strength, the size effect has a marginal effect on the stress-strain curves of the specimens.

The effects of AFRP sheets' orientation on the axial performance of circular concrete columns were studied by Vincent et al. [61]. A total of 24 concrete columns reinforced with AFRP sheets, with the concrete mix having different compressive strengths of 50 MPa and 80 MPa, were provided, and three different orientations of the fibers with 45, 60, and 75 degrees with respect to the longitudinal axes were considered. The results obtained from these experiments showed that decreasing the fiber angle diminishes the specimens' performance. An overview of the popular papers in the material systems category is given in Table 1.

3.2. Element types

The second category pertains to element types within the field of FRP in concrete. This section presents an extensive literature review that utilizes FRP's various structural elements, including slabs, beams, walls, columns, slab-on-ground (SOG), and foundations/footings. The applications of FRP in these elements can be categorized into two primary classes: repair applications and new construction. Further subdivisions can be made within the repair application category: externally bonded (EB) reinforcement and near-surface-mounted (NSM) reinforcement. The new construction class includes using FRP internal reinforcement to enhance capacity or prevent temperature and shrinkage cracking.

An examination of the acquired data from various papers illustrated that studies on beams account for 51.4% of all research in this category. Columns hold the second rank with a share of 32% (Fig. 11). Beyond these two popular topics, slabs and walls are the other two focus areas, contributing 9.34% and 4.77%, respectively, to the research in this category. FRP has been successfully used in designing and constructing different RC elements, but foundation/footing and SOG are topics yet to

Table 1

An overview of popular papers in the material systems category of FRP.

Reference	Objects of the research	Type	Results	Journal	Date
[62]	Evaluating the durability performance of GFRP bars	GFRP	The strength of bars wrapped in the mortar and placed in tap water was less affected than those put in a pore-water solution.	Journal of Composite for Construction	2009
[63]	Evaluate the longevity and durability of GFRP and BFRP bars.	B/GFRP	GFRP bars showed better performance, especially in higher temperatures, compared to the BFRP bars.	Construction and Building Materials	2017
[64]	Investigating effects of GFRP bars on the axial performance of a circular concrete column	GFRP	The performance of GFRP bars in concrete columns is similar to steel bars, and GFRP bars contribute to the axial capacity of columns by 5–10%	Journal of Composite for Construction	2013
[65]	Evaluating the bending and shearing responses of GFRP-RC beams	GFRP	Tensile rupture of GFRP bars dominated the flexural failure of concrete beams, and bond failure dominated shear failure.	Construction and Building Materials	2006
[66]	Evaluating effects of GFRP bars as reinforcement on shear performance of normal strength concrete beams	GFRP	The shear strength of the beams has nothing to do with the amount of longitudinal GFRP bars.	Journal of Composite for Construction	2001
[67]	Assessing the effects of sea sand and seawater concrete on the durability performance of GFRP and BFRP bars under sustained load	B/GFRP	The combined impact of sustained stress and temperature of the test environment of high-performance seawater sea sand concrete (HP-SWSSC) solution greatly affects the tensile strength retention of BFRP and GFRP bars, while Young's modulus of	Corrosion Science	2018

(continued on next page)

Table 1 (continued)

Reference	Objects of the research	Type	Results	Journal	Date
[68]	Evaluating the effect of compressive strength of concrete and different environmental solutions on tensile and shear performance of CFRP and GFRP bars	G/CFRP	the bars remains unaffected GFRP bars experienced strength loss when exposed to different solutions. However, CFRP bars demonstrated excellent durability during the exposure	Composite Structures.	2007
[69]	Assessing the performance of CFRP sheet as a strengthening material for concrete beams	CFRP	Using CFRP sheets results in increasing flexural strength and stiffness of concrete beams	Engineering Structures	2007
[70]	Suggesting a technique to estimate the deflection of concrete components reinforced with CFRP and GFRP bars	G/CFRP	The deflection of FRP-RC beams was higher than steel-RC beams. This is due to the lower elastic modulus of FRP bars compared to steel	Composite Structures.	2002
[71]	Investigating the effects of seawater sea sand concrete on the durability performance of C/G/BFRP bars in terms of Inter-laminar shear behavior	C/G/BFRP	As opposed to BFRP bars which showed the weakest performance in accelerated short-term results, GFRP bars accounted for the best performance.	Construction and Building Materials	2017
[72]	Evaluating the contribution of CFRP bars in compressive performance of concrete columns.	CFRP	CFRP bars contributed to increasing the axial capacity of the column by 12%.	American Society of Civil Engineering	2014
[73]	Estimating the bonding behavior of BFRP and GFRP bars under exposure to severe environmental circumstances	B/GFRP	The bond strength between the basalt-vinyl ester bar and the glass-vinyl ester bar and concrete deteriorates over time, whereas the bond strength of the basalt-epoxy bar to concrete remains relatively stable.	Materials and Design	2016
[74]	Evaluating the long-term	BFRP	The results showed that	Journal of Composites	2015

Table 1 (continued)

Reference	Objects of the research	Type	Results	Journal	Date
	performance of BFRP bars in corrosive solutions combined with sustained load.		acid, salt, and deionized water had less of an effect on the durability of BFRP bars than an alkaline solution.	for Construction	
[75]	Investigating the bond of G/C/AFRP bars to normal strength concrete.	G/C/AFRP	The compressive strength of concrete influences the bond strength. The bond strength of FRP bars is 40–100% of steel bars	Journal of Composites for Construction	2005
[76]	Assessing the bending performance of AFRP bars as a reinforcement for concrete beams	AFRP	The widest crack in concrete beams reinforced with AFRP bars was noticeably larger compared to beams reinforced with steel bars	Journal of Composites for Construction	2005

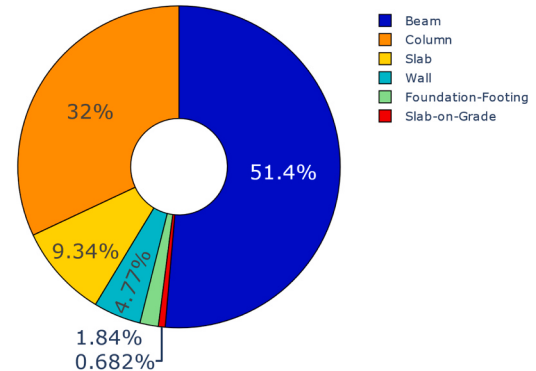


Fig. 11. Percentage of FRP-related papers in element types.

be fully explored. There is a recent interest in using FRP as secondary reinforcement in non-structural applications. For instance, FRP can substitute steel temperature and shrinkage reinforcement in plain footings, SOG, and walls [77]. Therefore, using FRP as secondary reinforcement can be another area of interest that researchers can explore.

3.2.1. Slab

3.2.1.1. Externally Bonded Reinforcement. Mosallam and Mosalam [78] conducted experimental and analytical studies to assess the effectiveness of RC slabs repaired or strengthened with CFRP and GFRP strips. A total of 10 concrete slabs were constructed and a unique method was used to apply a uniformly distributed load to the slab's bottom surface to cause the tension face at the top using high-pressure water bags. According to the results, both FRP systems successfully improved the strength of the repaired slabs to around five times that of the control slabs. Using FRP

strips to retrofit the slabs significantly increased the capacity of the unreinforced and reinforced control specimens by up to 500% and 200%, respectively. The computational models based on the finite element method accurately captured the experiments' results, and the steel reinforcement strains showed that CFRP composites significantly reduced the damage to slabs.

An experimental study was conducted by Yao et al. [79] to investigate the most common type of failure in flexural members strengthened on the tension side. This form of failure is generated by flexural cracks or flexural shear cracks and is known as intermediate crack debonding. Eighteen cantilever slabs plus four supported slabs were tested in this study. The type of FRP strips, width, and length were investigated. Apart from one slab with a strip width nearly equal to the width of the slab that failed due to concrete crushing, all the remaining slabs failed due to the debonding of FRP strips. The axial rigidity of strips significantly affects the debonding strain in strips. Due to the limited number of test results, these tests could not confirm the influence of the FRP-to-concrete width ratio. One of the cantilever slabs was reinforced with steel bars at mid-depth, and the load test showed that a sizeable concrete cover could negatively affect the debonding strain. The authors used the results to evaluate the precision of four available strength models. This evaluation showed that three out of four available strength models are not safe enough to be used in the design, and only one provides safer estimations of debonding strains. Despite this, it can also result in a conservative design.

In a paper by Smith et al. [80], an FRP anchor system was utilized to address debonding-related issues in RC slabs strengthened with FRP. Eight RC slabs comprising two reference slabs and another six slabs strengthened on the tension face with CFRP sheets and different FRP anchor configurations/types were constructed and tested. Compared to the unanchored reference slab, the best performance was observed as a 30% increase in capacity and a 110% increase in deflection. Moreover, the anchoring system increased the usable strain of FRP plates from 45% to 80% when compared to the unanchored reference slab. This study showed that the anchor type and positioning could affect the efficiency of the anchoring system. Additionally, the study indicated that positioning the anchors in the shear span is more efficient; using closer spacing of anchors decreases the debonding crack propagation rate, which in turn provides more considerable deflections. Lastly, the study showed that anchors with higher fiber content spaced close to the area of the maximum moment and anchors with less fiber content with tighter spacing and close to FRP plate-free ends provide greater improvements in both strength and deflection performance.

3.2.1.2. Near surface mounted. Fernandes et al. [81] conducted a study investigating CFRP laminate's bond and flexural performance in NSM strengthening. To achieve this objective, six slabs were built and subjected to a four-point flexural test encompassing monotonic and fatigue testing. When subjected to a fatigue test, the slabs reinforced with CFRP exhibited a smaller rise in deflection at the center than those without reinforcement. Monotonic tests performed after fatigue testing showed a slight increase in capacity and stiffness compared to control specimens. Concrete crushing on the compressive face of the slabs at mid-span was the most common mode of failure seen in slabs.

Kankeri and Prakash [82] investigated the performance of hollow core slabs strengthened with different strengthening techniques. Fourteen slabs were constructed, strengthened, and tested at a lower shear span-to-depth ratio (a/d) of 3.75 and a higher ratio of 7.50. The tension face of the slabs was strengthened with NSM CFRP laminates and EB CFRP. The slabs were also strengthened with a bonded overlay on the compression face. The result showed that the NSM approach increased the capacity of the slab by 49.4% at a low a/d ratio and 68.9% at a high a/d ratio. The EB approach increased the capacity of the slab by 16.9% at a low a/d ratio and 87.6% at a high a/d ratio. A combination of both techniques was also used, resulting in the highest capacity improvement

without considerably compromising ultimate displacement.

3.2.1.3. Internal reinforcement. Ospina et al. [83] an empirical investigation to examine how GFRP-RC two-way slabs behave under punching shear. They constructed and tested four slab-column joints as part of their experimental analysis. The results revealed that FRP's bond characteristics and stiffness affect the punching failure and that the higher stiffness of the bars increases the punching capacity. It was also observed that the failure does not initiate with FRP rupture. Moreover, it was concluded that the bond performance of bars influences load-deflection behavior. It was mentioned that the ACI 318-99 [84] and BS 8110-97 [85] are not appropriate for direct estimation of the punching capacity of FRP-RC slabs. Still, the equation by Matthys and Taerwe [86] is more reliable for evaluating the punching capacity of FRP-RC slabs.

El-Sayed et al. [87] evaluated the shear strength of FRP-RC one-way slabs. To this end, eight slabs were prepared to be tested under a four-point flexural test. Different factors, such as reinforcement ratio, type, and diameter of bars, were investigated. Sand-coated CFRP and GFRP rebars were chosen while five slabs were reinforced with GFRP and the rest with CFRP. All slabs failed in shear prior to reaching design flexural strength. The researchers noted that the shear strength of slabs increased as the reinforcement ratio was increased, with this effect being particularly prominent in CFRP-RC slabs. The study concluded that the axial stiffness of the bars influences the shear strength of concrete. The comparison of test results with ACI 440.1R-03 [88], CSA S806-02 [89], and JSCE recommendations [90] showed that the ACI guideline for the prediction of shear strength is too conservative.

3.2.2. Beam

3.2.2.1. Externally bonded reinforcement. Triantafyllou [91] studied the use of externally bonded FRP fabric in the shear strengthening of RC beams. The experimental investigation strengthened eleven beams with CFRP fabric having different fiber configurations and area fractions. Based on the findings of this research, the effectiveness of shear strengthening is maximized when the orientation of the fiber in the FRP fabric is near the direction perpendicular to the diagonal crack. In the analytical study, a model was developed to assess the extent to which fabrics enhance the shear capacity of a reinforced beam. It was demonstrated that increasing FRP axial rigidity can linearly enhance the efficiency of the strengthening technique.

An investigation has been conducted by Teng et al. [92] to study one of the main types of failure in RC beams strengthened with FRP plates, known as intermediate crack-induced debonding. This study aimed to establish a robust model designed explicitly for analyzing debonding failure in reinforced concrete (RC) beams strengthened with FRP plates. A debonding strength model was introduced, which offers a reliable estimation of the strength of RC beams when reinforced with FRP plates. Moreover, an approach incorporating the proposed model was also offered for strengthening beams lacking flexural capacity.

A finite element model was proposed by Huang et al. [93] for the RC beams strengthened with an FRP plate. The validity of the proposed model was validated using three different experimental studies in the literature: three-point bending tests, four-point bending tests, and a four-point shearing test. The analysis revealed that the diagonal cracks negatively affect the effectiveness of FRP strengthening. The numerical efforts show that ignoring the effects of tangential slip and normal separation at the interface of FRP plate and concrete results in over-estimating beam capacity and ductility. The friction coefficient can considerably affect the result obtained from the model, as an improper friction coefficient may alter the failure mode.

3.2.2.2. Near surface mounted. In a study by Lorenzis and Nanni [94], NSM CFRP rods were utilized for the shear strengthening of RC beams. A total of eight beams were tested in this study, including two control

specimens and six beams strengthened with different configurations of CFRP rods. Other variables include the presence of steel stirrups, CFRP rod spacing, and the layout of the CFRP rods. A 106% increase in the capacity of the beam was achieved using the NSM technique, and a simple model was also provided to predict the experimental results in this study. The predicted result from the proposed model was in good agreement with the experiments.

The effectiveness of NSM and EB for flexural and shear rehabilitation of RC beams was investigated in a study by Barros et al. [95]. CFRP composite was chosen for both strengthening methods. Flexural and shear strengthening were both investigated throughout the experimental phase. Three different beam series were prepared and tested in the flexural study, and each series includes four types of specimens: (1) a beam without flexural strengthening, (2) a beam with NSM CFRP laminate, (3) a beam with EB CFRP laminate, (4) and the last one with EB CFRP sheets. For shear strengthening, four series of beams were used, including (1) a beam lacking shear reinforcement, (2) a beam with steel stirrups as shear reinforcement, (3) a beam with U-shaped CFRP strips (4 and 5), and two beams with different configurations of CFRP laminates. Compared to the EB method, the results revealed that shear strengthening using the NSM approach provides better deformation, load-carrying capacity, and more ductile behavior. The flexural experiments also demonstrated that the NSM approach is the most efficient for increasing beam capacity.

3.2.2.3. Internal reinforcement. The bond strength of GFRP bars in RC beams was studied by Tighiouart et al. [96]. This study involved 64 RC beams and 18 pullout samples with two types of GFRP bars and four different diameters. In addition, three different embedment lengths were studied. It was concluded that using GFRP bars results in lower bond strength than steel, that adhesion and friction govern the bond behavior, and that a larger bar diameter provides lower bond strength. Increasing the embedment length helps the bar approach its ultimate strength. The top bar effect was also observed in GFRP-RC beams and a modification factor 1.30 is proposed to account for this effect. The authors also proposed a model for the ascending region of the bond-slip curve.

Tureyen and Frosch [97] proposed a simple approach for the shear design of FRP-RC beams. To validate their model, the authors collected data on 370 FRP-RC beams from 25 different studies found in the literature. The simplified equation provided in this study can be used for the shear design of steel-RC and FRP-RC beams. Using data collected from the literature, a comparison was made between the values derived using the proposed model and the design equation in ACI 318-02 [98]. This comparison demonstrated that the proposed equation provides a higher safety factor.

3.2.3. Wall

3.2.3.1. Externally bonded reinforcement. A study has been conducted by Almusallam and Al-Salloum [99] to investigate the feasibility and efficacy of EB GFRP sheets in repair or strengthening applications for unreinforced infill masonry walls under in-plane seismic and cyclic loads. The test findings illustrated that using GFRP sheets has great potential for improving the performance of infill walls by improving the deformation capacity and integrity of the wall subjected to in-plane seismic loading.

Binici et al. [100] investigated using EB FRP composites for retrofitting infill walls resisting lateral loads. This article presents the design and analysis of a structurally deficient building in Turkey. A simplified model was employed for prediction purposes to assess the performance of reinforced infill walls. The authors mentioned that this approach only applies if the structure has infill walls well-distributed in the plan with no past damage. The findings of this study are expected to aid decision-making in retrofitting applications since the model produces

realistic predictions of deformation and strength capacity.

To study the shear behavior of masonry walls retrofitted with EB FRP systems and textile-reinforced concrete (TRC), an experimental study has been carried out by Bui et al. [101]. A total of six masonry walls were constructed and strengthened with GFRP, CFRP, and TRC composites. These walls were then tested and subjected to shear compression, indicating a seismic demand. To enhance efficiency, mechanical anchorage connects composite strips to the foundation. It was concluded that anchorage is an essential component of the system and thus improves the performance of the walls. This study showed that the EB FRP system improves structural integrity with adequate reinforcement. Regarding ultimate displacement capacity, GFRP and TRC are more suitable than CFRP. The TRC system provides considerably higher ductility but lower lateral resistance.

3.2.3.2. Near surface mounted. An analytical study was conducted by Li et al. [102] to develop a model for estimating the efficacy of NSM FRP bars in retrofitting unreinforced masonry walls. Twelve walls were constructed and tested under diagonal compression to calibrate the model. The results show that using FRP in this application efficiently increases the structural performance of the walls, and the model agrees reasonably well with the experimental data. The most significant increase in shear capacity was around 80% in walls with bars inserted at bed joints. Reinforced walls have substantially superior ductility and provide more stability after failure, thus lowering the likelihood of collapse.

Al-Jaberi et al. [103] conducted a comparative study to assess the performance of masonry walls strengthened with Near-Surface Mounted (NSM) FRP and Fiber-Reinforced Cementitious Matrix (FRCM) systems. A total of twelve masonry walls were selected for the study, and these walls were reinforced either with NSM FRP using CFRP or GFRP bars or with FRCM using carbon or polyparaphenylene benzobisoxazole (PBO). The walls were subjected to cyclic loading, and the critical parameters investigated in the study included the bond pattern, type, and quantity of NSM bars or FRCM. The findings showed that the kind of fiber employed significantly impacted the wall's behavior. The highest flexural improvement was 97% and 75% for FRCM and NSM systems, respectively. In addition, a 38% and 62% increase in energy dissipation were observed using FRCM and NSM systems, respectively. Different failure modes, such as concrete block crushing, debonding of the NSM system or fabric, and fabric sliding in the cementitious matrix, were observed in this study.

3.2.3.3. Internal reinforcement. Ghazizadeh et al. [104] analytically investigated the possibility of hybridizing GFRP and steel rebars to reinforce concrete shear walls. Due to its lack of ductility, GFRP cannot be used in lateral load-resisting systems in areas vulnerable to high seismic risk. The hybrid design can enhance both ductility and self-centering features. The model was validated with the available data in the literature, and an effort was made to provide the most appropriate hybrid configuration. The study showed that the hybrid configuration exhibits comparable strength and ductility to conventional steel while possessing a greater self-centering capacity. The behavior of this system, subjected to four past earthquakes, was studied using nonlinear dynamic analysis. It was concluded that when constructed appropriately, the stiffness and serviceability of the aforementioned system were demonstrated to be equivalent to conventional systems.

In another paper by Ghazizadeh et al. [105], a parametric study was conducted on hybrid GFRP-steel RC shear walls. The model was first utilized to address the axial load presence and configuration of GFRP bars. The CSA A23.3-14 [106] was used to check the reliability of the numerical analysis. The self-centering features and financial aspects of using this hybrid system were also discussed. The outcome of this study can help practitioners design a more reliable and practical shear wall. Implementing GFRP rebars in the central half-width of the wall is

beneficial and results in ductile failure without GFRP rupture while demonstrating adequate strength and much smaller residual displacements. This study revealed that axial compression significantly enhances the self-centering of the walls. The reliability analysis showed that a strength reduction factor of 0.80 can be used to calculate the capacity of the walls in flexure.

3.2.4. Column

3.2.4.1. FRP tube. Mirmiran [107], evaluated 35 specimens under uniaxial compression with three different concrete strengths and three thicknesses of FRP jacket. Based on these experiments, Samaan et al. [108] proposed a model to estimate the bilinear stress-strain response of the concrete columns encased with FRP. The concept is based on a relationship between the rate of concrete dilatation and the hoop stiffness of FRP composite. The FRP and concrete material characteristics were closely related to the model's parameters. The model provides estimated stress-strain curves that are agreeable with the experimental results of prior research on FRP-encased and FRP-wrapped columns.

3.2.4.2. Externally bonded reinforcement. Mirmiran and Shahawy [109] studied the performance of concrete columns encased by FRP tubes to better comprehend their behavior and to propose an estimation of the improvement provided by the confining system for properly designing these elements. At the time of this article, the available models were simple extensions of the models proposed for RC columns. According to this study, the models in the literature typically overestimate the strength and result in unsafe designs. This study demonstrates that, in contrast to steel, FRP reduces concrete's tendency to dilate by reversing the volumetric strain direction.

Shahawy et al. [110] evaluated 45 CFRP-wrapped concrete cylinders constructed using two different concrete strengths and varying CFRP layers. This experimental effort was conducted to validate a confinement model that was proposed for GFRP tubes filled with concrete. It was determined that the adhesive bond between the CFRP layer and concrete does not considerably impact the confinement performance. Therefore, the model can be implemented for both FRP tubes and FRP wrap systems. The same model can also be used for both CFRP and GFRP while considering the concrete's potential to dilate depending on the composite material stiffness. A reliability analysis is required to determine the wrap's effective hoop rupture strain by choosing the right confidence level for the design. The wrap considerably improves the ductility of the system by restricting the concrete's lateral dilation.

3.2.4.3. Near surface mounted. In their study, Mostofinejad and Moshiri [111] developed an experimental investigation aimed at evaluating the efficacy of the grooving method (GM) in enhancing the compressive performance of reinforced concrete (RC) columns. The novelty of this method is its ability to restrict the global buckling of composites. The GM method proposed in this study was compared to NSM and EB techniques, and 22 columns were evaluated under compression. According to the results, the GM technique significantly increased the columns' ultimate loads. Moreover, it was shown that using the GM approach considerably raised composites' maximum compressive stress capacity according to the mean compressive stresses of carbon fibers.

The hybrid use of NSM CFRP laminate and EB CFRP fabrics was used by Chellapandian et al. [112] to improve the ductility and strength of concrete columns. A total of 10 square concrete columns were constructed and evaluated under axial compressive force to comprehend the efficacy of the strengthening methods. The available models from published literature were utilized to estimate the columns' capacity. A strong relationship was observed between the calculated capacity and the experimental results. Compared to the NSM technique and confinement using CFRP fabric, the hybrid strengthening system improved capacity, stiffness, and ductility more remarkably. A

comparison of this result to the control specimen showed that the ultimate strength and ductility rose by around 26% and 50%, respectively. The confinement of CFRP fabrics helped postpone the NSM laminates' micro-buckling. This behavior was highlighted by the failure mode and damage pattern observed in the hybrid method.

3.2.4.4. Internal reinforcement. Elmessalami et al. [113] conducted a critical review of the literature on FRP-RC columns to determine knowledge gaps and paths for future studies. The analysis of existing literature data and the precision of proposed design models for predicting FRP-RC columns' behavior recommend that code officials consider the effectiveness of FRP in concrete members under compression.

Elmessalami et al. [114] evaluated twelve concrete columns with longitudinal FRP reinforcements under concentric and eccentric loads. This study considered various factors, including FRP bar type, reinforcement ratio, and load eccentricity-to-width ratio. The experimental results revealed that both BFRP and GFRP-RC columns exhibited roughly similar load-carrying capacity while being lower than steel-RC columns. The analytical study demonstrated that neglecting the contribution of FRP bars to the strength of columns results in a conservative design.

A study was carried out by Afifi et al. [115] on circular GFRP-RC columns to investigate the effect of reinforcement type, ratio, volumetric ratio, diameter, and spiral spacing on the axial capacity of columns. Twelve columns were constructed and tested under concentric compressive loads: two steel-RC columns, one plain concrete column, and the remaining nine columns comprised of GFRP rebars or spirals. This study demonstrated that up to 85% of the capacity of both types of reinforcement—GFRP and steel—have a linear load-strain relationship. An accurate prediction of nominal capacity was made by assuming the compressive strength of the GFRP bars to be equal to 35% of their tensile strength. The average capacity of GFRP-RC columns was 7% lower than that of steel-RC columns. In specimens with smaller volumetric ratios or larger spiral spacing, the failure was governed by buckling of longitudinal reinforcement.

On the other hand, the failure mode of well-confined columns reinforced with GFRP was concrete core crushing and spiral rupture. The GFRP reinforcement contributed between 5% and 10% to the peak load capacity of the section, and the reinforcement ratio did not substantially affect the capacity but considerably affected the ductility. Spirals with a smaller diameter and closer spacing provide ductile post-peak behavior.

Mohamed et al. [116] evaluated the FRP-RC column's performance in compression to address the gap related to the compressive behavior of FRP-RC columns in the available design codes and specifications. A total of 14 columns were constructed and tested under concentric axial compression. In this study, sand-coated CFRP and GFRP reinforcements were used as longitudinal reinforcement, while the columns were also confined with the same types of FRP in two different configurations of spirals and hoops. Different parameters such as FRP type, volumetric ratio, confinement reinforcement type, and length of hoop lap were investigated in this study. According to the outcome, G/CFRP-RC columns behaved similarly to steel-RC columns. Utilizing FRP hoops and spirals by CSA S806–12 provisions results in adequate restraint to prevent buckling of longitudinal FRP reinforcement and satisfactory confinement of concrete in the core of the column after reaching the peak. The findings of this study can be applied to the codes and design guidelines to allow for the use of G/CFRP hoops and spirals. It was observed that FRP hoops can be as effective as spirals; thus, there is an insignificant difference in their contribution to strength and ductility. A compressive strain value of 0.4% and 0.7% was observed in GFRP and CFRP, respectively. These values demonstrate that FRP bars successfully resisted the compressive load. It was suggested that to prevent pullout or slippage, a splice length of 20 times the diameter of the hoop is adequate.

3.2.5. Slab-on-ground

The most significant concrete construction with GFRP bars worldwide is a flood-mitigating channel constructed in Saudi Arabia by Villen Salan et al. [117]. The base slab of this 21-kilometer-long flood channel is SOG reinforced with GFRP reinforcement. Due to the severe environment in which the channel was built, which can cause steel corrosion, followed by concrete cracking and spalling, GFRP was chosen. The current design with GFRP rebars is expected to provide over 100 years of service life. A total of 10 million linear meters of GFRP rebar were utilized in this project. GFRP provided a solution for a durable structure with a longer service life. It also reduced the construction time. The labor was decreased due to the lower weight of GFRP compared to steel, and there was no need to use heavy equipment to move the bars or implement them.

In a study by Roghani et al. [118], the use of GFRP mesh in constructing non-structural SOG was investigated, and short-term behavior and constructability aspects were documented. The slab was part of a two-story residential building. Due to the structure's proximity to salt water, the use of GFRP increased the service life of the slab. This study

confirmed that the lightweight of the material and the mesh layout could facilitate the project by reducing construction time. It was observed that the reinforcements could return to their original level after mesh implementation if the workers walked on them.

Al-Zahrani et al. [119] tested 12 SOG specimens to evaluate the shear punching capacity under concentrated loads. The slabs were placed on extruded polystyrene foam to simulate the condition of a dense sand subgrade. The effects of reinforcement type, spacing, depth of reinforcement, concentrated load point of action, and loading type were investigated in this study. The capacity of slabs reinforced with GFRP was between 9% and 21% less than that of steel-reinforced slabs. In specimens with 200 mm rebar spacing, the deflection at failure in GFRP slabs was roughly 14% more than its steel counterpart. In specimens with 200 mm bar spacing, the cracking load in slabs with sand-coated GFRP was higher than in steel-RC slabs. In steel-RC slabs, it was higher than in slabs with ribbed GFRP bars. In bar spacing of 300 mm slabs, the steel-reinforced slab exhibited the lowest cracking load but demonstrated the highest punching shear capacity compared to GFRP rebars. The authors also developed an equation to estimate the shear

Table 2

An overview of popular papers in the element types of categories in FRP.

Reference	Objects of the research	Type	Results	Journal	Year
[122]	Estimate deflection in FRP-RC elements under flexure using simple approaches	Slab	Approaches were validated with experimental results, and a good agreement was observed between the analytical method and experimental data	Composite Structures	2002
[123]	Investigate the use of NSM CFRP rods to increase the capacity of RC two-way slabs	Slab	The NSM technique enhances the capacity of RC slabs, and NSM provides better ductile performance than that of the externally bonded technique	Construction and Building Materials	2008
[124]	Investigate blast resistance of RC slabs retrofitted with FRP plates	Slab	Applying externally bonded FRP plates to the compression side of an RC slab enhanced blast resistance and ductility	Engineering Structures	2009
[125]	Comparing the flexural behavior of FRP-RC and steel-RC beams	Beam	Crack pattern and spacing are similar in FRP and steel-RC beams at low loads, but more cracks with larger widths are observed in FRP-RC beams	ACI Structural Journal	1996
[126]	Investigate the effectiveness and performance of NSM FRP-retrofitted T-beams	Beam	Results revealed that utilizing NSM FRP strips and bars is feasible and enhances the stiffness and flexural capacity of RC beams	ACI Structural Journal	2004
[127]	Study the feasibility of using basalt sheets for strengthening beams	Beam	Basalt sheets can be a promising material for strengthening. The impact of strengthening with one layer was not noticeable but improved dramatically as the number of layers rose	Composites Part B: Engineering	2005
[128]	Investigate the flexural capacity of masonry walls strengthened with GFRP strips	Wall	GFRP strips supplied a capacity roughly equal to No. 5 steel rebars spaced 24 in. apart at the wall center. GFRP fracture and delamination were the observed failure modes	Journal of Composites for Construction	2001
[129]	Evaluate the performance of FRP bars with different cross-sectional shapes in strengthening URM walls	Wall	This technique markedly enhanced the capacity, kept the aesthetics, and provided minimal installation time	Composites Science and Technology	2006
[130]	Evaluate (experimentally and numerically) the seismic performance of a hybrid steel-GFRP-RC low-rise shear wall	Wall	Hybrid design helps reduce residual displacements and provides better self-centering behavior compared to the steel-RC wall. The proposed numerical model successfully predicted the cyclic response	Journal of Composites for Construction	2018
[131]	Develop a stress-strain model for FRP-confined concrete	Column	Several critical issues, such as real hoop strains at FRP rupture, adequacy of FRP confinement, and influence of FRP stiffness on the ultimate axial strain, were addressed	Construction and Building Materials	2003
[132]	Investigate the performance of RC columns reinforced with NSM subjected to simulated seismic loads	Column	The NSM FRP is a promising option for improving flexural capacity of RC columns under seismic loading.	ACI Structural Journal	2009
[133]	Studied the influence of tie spacing and configuration in GFRP-RC columns under concentric loading	Column	It was observed that the GFRP-RC columns could withstand loads comparable to or greater than those of steel-reinforced columns	ACI Structural Journal	2012
[117]	Field implementation of GFRP rebars to increase the service life of the flood channel	SOG	GFRP offered a solution for a durable structure and accelerated construction time. Labor was reduced, and implementation did not require heavy equipment	Concrete International	2021
[134]	Report construction and in-situ load testing of a GFRP-RC ground-supported slab	SOG	GFRP is reliable, durable, and increases productivity. Concrete and GFRP experienced larger stress and strain when the slab was centrally loaded; larger deflections were observed in the edge-loaded slab	Structures	2022
[119]	Evaluate the punching shear capacity of GFRP-RC slabs-on-ground under concentrated loads	SOG	The capacity of GFRP-RC slabs was lower and showed larger deflections. An equation was developed to estimate punching shear capacity	Engineering Structures	2023
[120]	Evaluate GFRP-RC footing behavior with lightweight concrete with/without shear reinforcement	Footing	Due to the weaker bond between lightweight concrete and GFRP, strain in GFRP was lower than in normal-weight concrete footings	Materials and Structures	2017
[121]	Investigate the behavior of isolated GFRP-RC footings subjected to concentric load	Footing	Wider crack widths and larger deflections were observed in GFRP-RC footing and ultimate punching shear capacity was lower than in steel-RC footings	Journal of Al-Azhar University Engineering Sector	2022

punching capacity of GFRP-reinforced SOG. They validated the equation with data from the literature and experimental findings from their research.

3.2.6. Foundation-footing

Oskouei et al. [120] conducted an experimental study to evaluate a full-scale lightweight concrete single footing reinforced with GFRP. Seven footings were constructed, one of which was cast with normal-weight concrete and the others with lightweight concrete. The GFRP rebars experienced the maximum strain at the location of the base plate. The strain of GFRP rebars in lightweight concrete footings was lower than in normal-weight concrete footings due to the weaker bond produced between lightweight concrete and the GFRP bar.

To investigate the punching shear performance of GFRP-RC concrete footings, a total of eight isolated footings were tested by Saleh et al. [121]. Half of the specimens were reinforced with GFRP, and the other half served as reference specimens reinforced with steel reinforcement. Reinforcement ratio, reinforcement type, and shear span-depth ratio were the parameters investigated in this study. More considerable deflections and wider cracks were observed in footings reinforced with GFRP reinforcements. The ultimate punching shear capacity of GFRP-RC slabs was lower than that of their steel counterparts. This reduction in capacity varied between 16.25% and 33.97% while being affected by the longitudinal reinforcement ratio. Table 2 presents a synopsis of the critical research papers focusing on different categories of element types in FRP.

3.3. Applications

In this part, four applications of FRP material in structural engineering that impact the construction industry will be summarized. The first is FRP grids, structural reinforcement materials that provide load-bearing capabilities and are often employed in applications such as bridge decks and concrete pavements. In these instances, their high stiffness and low weight offer significant advantages. In addition to FRP grids, FRP bars, strips, and tendons are used to reinforce concrete structures. FRP bars offer excellent tensile strength and increasingly replace conventional steel reinforcement in various applications.

On the other hand, FRP strips are utilized to strengthen the shear of concrete beams and columns. Furthermore, FRP tendons of prestressed fibers encased in a protective sheath are utilized in post-tensioning applications, increasing strength and minimizing structural deformation. The section discussing applications is divided into four categories, as previously mentioned. A simultaneous representation of the percentage and number of papers is provided in Fig. 12. Based on this data, it is discerned that a major portion of the research, i.e., 67.76%, is associated with bar applications.

Regarding rankings, the following prominent category is strip, encompassing 24.24% of all publications. However, grid and strand

have garnered considerably less attention at 5.34% and 2.66%, respectively. These categories are not currently hot topics in this field, indicating an area of potential opportunity and need for further research/development in the future.

3.3.1. Bar

The most widely used building material is concrete reinforced with steel. However, it is generally accepted that steel reinforcement corrosion can lead to the deterioration or failure of structural components under certain environmental circumstances. Repairing and reinforcing corroded concrete structures is an annual global expense in the billions, prompting studies to develop new approaches.

To evaluate the bond behavior of FRP bars under direct pullout conditions, Achillides and Pilakoutas [135] conducted a series of experimental tests using various types of FRP bars embedded in concrete specimens. The tests involve direct pullout conditions where the FRP bars are subjected to axial tensile forces until failure. The experiments are carefully designed to investigate the influence of different parameters on the bond behavior, such as bar diameter, embedment length, concrete strength, and surface preparation. The results of the experiments are then presented and analyzed. The authors discussed the bond strength, slip behavior, and failure modes observed in the tests. They also examined the effects of parameters on bond behavior. Via these tests, insight into the behavior of FRP bars in direct pullout situations was provided. The bond failure of FRP bars differs from steel bars with concrete strengths above 30 MPa, causing surface peeling of the bar. On the other hand, concrete strengths below 15 MPa lead to concrete crushing in front of the bar deformations, indicating that the bond strength of FRP bars is influenced by interlaminar shear strength rather than concrete strength.

The bending performance of concrete beams reinforced with FRP bars was studied by Benmokrane and Masmoudi [136]. It was observed that the crack pattern and spacings are similar in FRP and steel-RC beams at low load, but more cracks with larger widths occur in FRP-RC than in their steel counterparts. This study was conducted in 1996 before developing a code or guideline for designing GFRP-RC beams. The authors mentioned that even though the crack width is more significant than steel reinforcement, the acceptable crack width limit can be changed due to the corrosion resistance of FRP bars.

In 2012, Tobbi et al. [137] carried out a comprehensive experimental program consisting of concrete columns reinforced with GFRP bars. The columns are subjected to axial and lateral loads to evaluate their behavior under different loading conditions. The experimental variables include the reinforcement ratio, bar diameter, and longitudinal and transverse reinforcement configuration. The study presents and investigates experimental outcomes regarding load-bearing capacity, vertical deformations, horizontal deformations, failure patterns, and cracking trends. These insights shed light on the performance of GFRP-RC columns. The authors also compared the performance of GFRP-RC columns with conventional RC columns, highlighting the advantages and limitations of GFRP reinforcement. They discussed the potential benefits of using GFRP bars, such as increased durability, reduced maintenance costs, and improved sustainability.

To develop a straightforward design method for FRP-reinforced beams and assess the feasibility of using a unified approach for steel and FRP-reinforced members, Tureyen and Frosch [97] present a comprehensive review of the factors influencing shear behavior. The study introduces a model for determining the concrete's contribution to shear strength in reinforced concrete beams, which is validated by comparing calculated shear strengths with experimental results from 370 specimens. They discussed various parameters, including concrete material properties such as compressive strength, aggregate characteristics, and other structural considerations such as shear reinforcement, loading conditions, and member geometry. The paper emphasizes the significance of considering material-related and structural factors to accurately predict and evaluate concrete shear strength. The model is

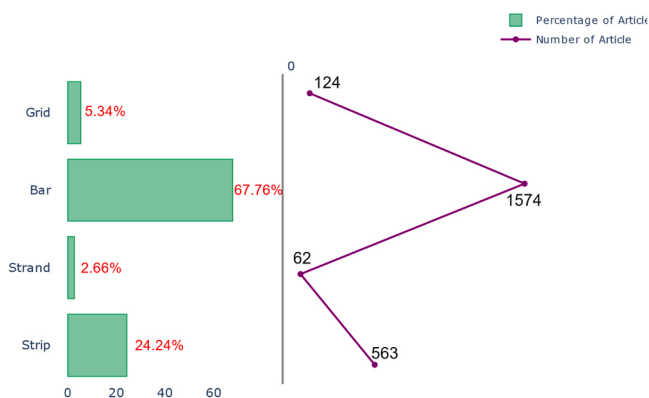


Fig. 12. Percentage of applications in terms of publishing the paper in FRP.

further simplified to yield a design equation that provides conservative values across various factors affecting shear strength. Based on those findings, they proposed an equation that can be employed for designing reinforced concrete beams with both steel and FRP reinforcement.

FRP stirrups and hoops, a critical component in reinforced concrete structures, offer unique characteristics compared to traditional steel reinforcements. These stirrups, crafted from anisotropic materials, exhibit exceptional longitudinal strength while their lateral strength remains comparatively weak. This attribute is particularly significant as it influences the design and application of FRP bars, especially when they are bent to form stirrups, thereby affecting their overall tensile strength and structural integrity [138].

The bending process of FRP bars is crucial as it can significantly reduce their strength at the bend portions, primarily due to the anisotropic nature of the FRP materials. The American Concrete Institute's guidelines, specifically ACI 440.6, stipulate that only FRP bars made with thermosetting resin are permissible, and bending is allowed solely when the resin is in its liquid state [139]. This is because the manufacturing process can lead to a 'flattening' at the bend's corner, reducing the bar's thickness in that area and causing the internal fibers to extend unevenly. Such alterations result in radial stresses and potentially premature failure when the bar is under tension. Unlike steel stirrups, which undergo plastic deformation to accommodate bends without compromising the yield stress, FRP bars cannot rely on such plasticity and thus require careful consideration in their application [140].

To mitigate these challenges, ACI 440.1 provides specific detailing requirements for using bent FRP reinforcing bars or spirals as shear reinforcement. It is recommended to avoid sharp bends that can lead to stress concentrations and significantly lower the tensile strength, potentially to as low as 50% of the bar's capacity. The guidelines suggest a minimum bend radius of three times the bar diameter and a minimum tail length to ensure effective stress transfer to the concrete. Additionally, the stipulated maximum stirrup spacing ensures interception of potential shear cracks, maintaining the structural integrity of the reinforced concrete member. These specialized requirements underscore the meticulous design and implementation need to utilize FRP stirrups to leverage their benefits while addressing their unique material properties [141].

3.3.2. Strip

Fiber-reinforced polymer strips and sheets represent a groundbreaking advancement in structural engineering, offering innovative solutions for reinforcing and rehabilitating various infrastructural elements. These materials are pivotal in enhancing buildings' and bridges' structural integrity and longevity, providing essential support and resistance against environmental and mechanical stresses. Near-surface mounted FRP rods and strips effectively prevent delamination failures, offering a reliable alternative to externally bonded reinforcements, especially in areas vulnerable to damage. This method is ideal for flexural strengthening in negative moment regions of slabs and decks. Initiated in Europe in 1947, the technique's efficacy, confirmed by Asplund's 1949 tests, shows that steel bars embedded in grooves perform similarly to externally bonded reinforcements [142].

In research conducted by Bank and Arora [143], the load-bearing capacity and functionality of RC beams strengthened with mechanically connected FRP strips were investigated. The purpose of Bank and Arora's study is to compare the effectiveness of these strengthened beams with more traditional strengthening techniques. RC beams were experimentally tested and strengthened with FRP strips to achieve this. The critical parameters studied in the research include load-deflection response, crack propagation, ultimate load capacity, and failure modes of the strengthened beams. The experimental results were analyzed and compared to those of traditionally strengthened RC beams. The findings indicate that applying mechanically fastened FRP strips improves the load-carrying capacity and stiffness of the beams. The FRP strips

successfully slow down the development of cracks while increasing the flexibility and overall functionality of the beams. The study mentioned the failure types detected in these strengthened beams, which included FRP debonding, concrete crushing, and FRP rupture. The behavior of the FRP-strengthened beams is analyzed while providing insights into the effectiveness of the mechanically fastened FRP strips and their interaction with the concrete substrate.

Yazman et al. [144] conducted several experiments on RC T-beams that were strengthened with either anchored or non-anchored CFRP strips applied to the shear span. The results suggest that both techniques successfully enhance the T-beams' ability to withstand shear forces. However, the behavior and failure modes of the two techniques differ with variations in load-displacement response, crack propagation, and debonding mechanisms. The paper discusses the observed failure modes, such as CFRP debonding, concrete cover separation, and crushing. The mechanisms and factors influencing the shear strengthening efficiency of anchored and non-anchored CFRP fabrics are analyzed while providing insights into their performance and applicability for T-beam strengthening. The choice between the two methods depends on structural requirements, design considerations, and practical constraints.

Regarding the performance of RC beam-column joints, which are reinforced with FRP strips in different configurations, Mukherjee and Joshi [145] studied them under cyclic loading, simulating seismic forces. The critical parameters studied in the research include joint response, deformation characteristics, strength, and failure modes under cyclic excitation. The study concludes that both glass and carbon composite materials are adequate for seismic retrofitting and rehabilitating RC joints. These substances substantially boost the strength of the joints, irrespective of the strengthening specifications or the extent of damage. Using these composites can substantially increase the yield load of the joints, and the initial stiffness depends on the number of overlays applied to the joint area. Joints strengthened with CFRP are stiffer than those reinforced with GFRP. Employing a small number of composites can also increase the joints' energy absorption capacity. Experiments on repaired samples show that FRP maintains the joints' original strength and significantly boosts the joints' yield load, initial stiffness, and energy absorption capacity.

3.3.3. Strand

In the realm of infrastructure and building construction, traditional steel cables have long been the preferred choice. These steel tendons, consisting of high-strength wire strands arranged in specific configurations, offer commendable benefits such as remarkable tensile strength, anchorage, and a high elastic modulus. However, despite their advantages, conventional steel tendons suffer from several drawbacks, including sag effects, severe corrosion damage, low carrying efficiency, poor fatigue performance, and excessive self-weight. FRP strands have emerged as an alternative due to high fatigue resistance, anti-corrosion capabilities, and an impressive strength-to-weight ratio. Consequently, FRP strands have found applications in reinforcing new structures and retrofitting and strengthening existing structures. Despite the large amount of research conducted on the use of FRP cables in construction, there still needs to be a significant gap between the study findings and the practice of employing prestressed FRP strands in constructing buildings and other types of infrastructure. This disparity may be explained by several factors, including the mechanical properties that FRP strands possess, the limitations when it comes to implementing research findings, and the complex structural concerns associated with using FRP strands [146].

Over the last three decades, many studies have been done on FRP strips' different anchor methods. One of the pivotal studies on the mentioned topic was done by Nanni et al. [147]. An experimental investigation was carried out to assess the mechanical performance of ten different aramid, glass, and carbon FRP strips. The focus was on evaluating the impact of the manufacturer-recommended anchorage device. The paper discusses FRP strip-anchor systems' design and

construction aspects, including selecting FRP tendons, anchor types, and installation techniques. It also addresses the challenges and considerations of using FRP materials in prestressed concrete applications. Finally, they conclude that the anchor primarily controls the ultimate load capacity rather than the tendon, which indicates the potential for improving anchor efficiency. The three classes of anchor systems (wedge, resin potted, and spike) presented various advantages and disadvantages with varying installation complexity.

Twenty years later, in 2015, Wang et al. [148] utilized a novel numerical analysis study to simulate and analyze the behavior of the anchor system under various loading conditions. A novel anchor for large-sized FRP cable with multiple tendons is proposed, and the key factors that influence anchor efficiency are optimized using the finite element method (FEM). The results of the numerical study are presented and discussed while focusing on parameters such as stress distribution, load transfer, and overall structural behavior. The analysis focused on four key factors that impact anchor efficiency: modulus variation, conical degree, anchor length, and the thickness of the load transfer component. The findings demonstrate that the proposed anchor offers significant advantages in terms of bonding through the integration of the load transfer component and FRP cable. Additionally, the anchor achieves a variable modulus of the load transfer component by altering the winding angle of the fiber roving.

Braimah et al. [149] examined of the performance and durability of concrete beams containing unbonded CFRP strands subjected to cyclic loading conditions. They aim to understand the post-tensioned beams' fatigue behavior, load-carrying capacity, and failure modes. Experimental tests were conducted on concrete beam specimens post-tensioned with unbonded CFRP tendons. The beams were subjected to cyclic loading to simulate fatigue conditions. The critical parameters studied in the research include fatigue life, crack propagation, and changes in beam behavior under repeated loading cycles. The research concludes that post-tensioned concrete beams with unbonded CFRP tendons can enhance fatigue resistance. The use of CFRP tendons offers potential benefits in terms of increased durability and prolonged service life compared to traditional steel tendons.

3.3.4. Grid

FRP grids find another application in controlling and preventing the formation of plastic shrinkage cracks in concrete elements, which commonly occur during the early stages of curing when rapid moisture loss occurs. Yost et al. [150] conducted research on the flexural performance of concrete beams reinforced with a 2D FRP grid, focusing on the impact of longitudinal FRP reinforcement levels. They tested beams under varying reinforcement conditions, comparing the results with theoretical predictions based on standard concrete procedures. The study found accurate predictions for flexural capacity but not for shear strength, with deflection accuracy depending on the reinforcement ratio. Despite some discrepancies in stiffness predictions, a bilinear concrete model provided a reliable deflection analysis. The FRP grid effectively maintained force transfer, with specific cracking patterns and no deterioration in structural integrity.

Shao et al. [151] examines the mechanisms and challenges associated with plastic shrinkage cracking while emphasizing the advantages of CFRP grids as a reinforcement material in mitigating this issue. The researchers conduct experiments involving casting concrete specimens with and without CFRP grids under controlled environmental conditions that induce plastic shrinkage cracking. The performance of the specimens is assessed through visual observations, crack width measurements, and crack pattern analyses. The results demonstrate that incorporating CFRP grids significantly reduces the occurrence and severity of plastic shrinkage cracking by effectively distributing tensile stresses and impeding crack propagation. This contributes to the overall durability and integrity of the concrete. The paper also addresses design considerations for implementing CFRP grids as a preventive measure against plastic shrinkage cracking. Overall, the study highlights the

potential of CFRP grids as an effective solution in controlling this cracking in concrete, providing valuable insights for their practical application to enhance concrete structures' performance and service life. Table 3 provides a summary of the significant research papers related to applications in FRP.

The study examined by Fang et al. [152] focuses on the flexural behavior of composite concrete slabs reinforced with FRP grid face sheets. Through experimental tests, the researchers found that these composite slabs exhibited high load-carrying capacity, enhanced flexural strength, and stiffness compared to conventional RC slabs. The FRP grid face sheets effectively distributed and resisted applied loads while providing confinement, allowing for gradual post-peak response and increased deflection capacity. The study also identified various failure modes, including flexural cracking, debonding, and rupture of FRP grid elements. This led to design recommendations for reinforcement ratio, spacing, and supplementary reinforcement. The findings contribute to the understanding and design optimization of composite concrete slabs reinforced by FRP grid face sheets, applicable to various structural applications requiring improved flexural performance and durability.

To compare the flexural performance of concrete slabs reinforced with FRP grids with traditional steel reinforcement, experimental tests were conducted by Matthys and Taerwe [153]. One-way bending loads were applied to test specimens strengthened with steel bars or FRP grids. Critical aspects such as load-deflection response, cracking behavior, and the slabs' ultimate load-bearing capacity were the study's primary focus. Steel-reinforced and FRP-grid-reinforced slabs were subjected to rigorous experimentation, and the results were thoroughly examined and compared. The findings indicate that the FRP grid reinforcement can effectively improve the flexural behavior of the concrete slabs. The FRP grids contribute to increased load-carrying capacity, enhanced crack resistance, and improved overall performance of the slabs.

Additionally, the study examines the failure modes observed in both types of slabs and discusses the mechanisms behind the behavior. It explores the differences between steel reinforcement and FRP grid reinforcement in terms of stiffness, ductility, and resistance to cracking. The research findings provide valuable insights into the behavior of FRP grid-reinforced concrete slabs and contribute to the advancement of sustainable and durable construction practices.

In 2020, Sha X et al. [154] carried out research on performance of concrete columns with FRP grids and a square section under axial compression. FRP grids were placed transversely along the perimeter of the columns to strengthen them. The study's main goal was to investigate the columns' load-deformation response, ultimate load-bearing capability, and observed failure modes. The findings indicate that including FRP grid reinforcement significantly improves the axial compressive behavior of the columns. The FRP grids contribute to increased load-carrying capacity, enhanced ductility, and resistance to premature failure. The paper discusses the observed failure modes in the FRP-strengthened columns, such as FRP rupture, concrete crushing, and debonding between the FRP grids and the concrete. The mechanisms behind these failure modes are analyzed, providing insights into the behavior of FRP-strengthened concrete columns under axial compression. Table 3 summarizes the significant research papers related to the 'applications' category.

4. Discussion

FRP composites in concrete have had a significant impact on developing civil engineering during the past few decades. FRP composites are distinguished by their superior mechanical capabilities and their chemical resistance. Due to its characteristics, FRP is a promising alternative to conventional reinforcing materials in concrete constructions. FRP materials are frequently lauded for their superior qualities compared to traditional materials, which include:

- Exceptionally high strength-to-weight ratio.

Table 3
An overview of popular papers in the applications category.

Reference	Objects of the research	Type	Results	Journal	Year
[155]	Examining the bond between FRP bars and concrete. Investigating the impact of factors such as fiber type and outer surface characteristics on the performance of the bond.	Bar	FRP smooth rods are inadequate for use in reinforced concrete structures due to low bond strength caused by friction mechanisms and damage to the bar surface.	Journal of Composites for Construction	1997
[156]	Investigate the effect of different environmental conditions, namely water, simulated alkaline pore solutions, saline solution, and an alkaline solution combined with chloride ions on FRP rebars.	Bar	Durability performance FRP can be improved by selecting suitable constituents, manufacturing quality, and considering the interphase between fibers and matrix.	Composite Structures	2007
[157]	Evaluate different types of strengthening techniques with FRP to strengthen RC T-beams.	Bar	NSM-FRP improves the stiffness and flexural capacity of RC beams, demonstrating practicality and higher strength capacity compared to externally bonded FRP strips.	ACI Structural Journal	2004
[158]	The flexural performance of simply supported concrete beams reinforced with a two-dimensional (2D) FRP grid under four-point monotonic loading was assessed.	Grid	The prediction of flexural capacity aligns well with the guidelines outlined in ACI 318–95.	Journal of Composites for Construction	2001
[159]	Evaluating the mechanical performance and durability of a novel FRP-UHPC composite plate through flexural and tensile testing.	Grid	FRP-UHPC composite plate exhibits strong interaction, enhanced flexural and tensile capacities,	Composite Structures	2021
[160]	Investigating shrinkage strains of Infra-lightweight concrete (ILC) reinforced with CFRP and GFRP.	Grid	The FRP grid dramatically lowers shrinkage strains.	Construction and Building Materials	2020
[161]	Investigate the performance of RC joints reinforced with FRP under simulated seismic loads.	Strip	Externally bonded FRP improves the strength, energy dissipation, and stiffness of poorly detailed RC joints under seismic loads.	Journal of Composites for Construction	2003
[162]	Assess the bond characteristics of NSM CFRP strips.	Strip	Presenting an analytical solution, offering a closed-form method to predict interfacial shear stresses.	Journal of Composites for Construction	2003
[163]	Investigate the performance of the NSM technology for shear strengthening of concrete beams.	Strip	The NSM technique using CFRP strips was found to be the most effective for both flexural and shear strengthening of reinforced concrete (RC) beams.	Cement & concrete composites	2007
[164]	Describing a Life Cycle Cost (LCC) analysis to evaluate the cost of four distinct alternative reinforcement bars for the design of the Halls River Bridge.	Strand	The Epoxy-coated Steel alternative is not cost-effective for corrosion resistance, while Carbon Steel has lower initial construction costs compared to FRP and Stainless Steel.	Structure and Infrastructure Engineering	2020
[165]	Investigating the effectiveness of a new anchorage technique for FRP shear-strengthened RC T-beams with CFRP strands.	Strand	Beams anchored with CFRP strands contribute much more to shear resistance than beams reinforced with CFRP sheets and CFRP L-strips without strands.	Journal of Composites for Construction	2015
[166]	Conducting LCC and Life-Cycle Assessment (LCA) analyses for an FRP-RC/PC bridge located in Florida.	Strand	The FRP-RC alternative has a shorter service life but requires less maintenance, while also offering long-term economic benefits and lower environmental impacts compared to the Carbon Steel-RC alternative.	Advances in Structural Engineering	2019

- Remarkable resilience in harsh environments.
- Simplicity and rapidity of setup.
- Electromagnetic transparency and electrical non-conductivity
- The potential to customize mechanical attributes by selecting fiber and fiber orientation is suitable.
- Excellent fatigue features (especially for CFRP).
- Limited thermal conductivity.

However, like any material, FRP has its drawbacks. It is essential to consider the material’s potential for thermal expansion and its fire resistance. FRP bars cannot be bent on-site. In addition, FRP manufacturing is less evolved than the steel industry, and thus, there is also a supply chain issue to consider. Therefore, detailed planning is required to prevent construction downtime. Solutions to these issues exist, and FRP is still being considered when selecting the ideal material for a project. Fig. 13 shows that element types comprise 50% of the total publications, material systems are 36% of the distribution, and applications account for 14% of the total publications. These proportions indicate the focus areas in FRP research related to concrete, with ‘Elements’ emerging as the primary area of interest. This figure shows that ‘Elements’ dominate the field, with half of the research dedicated to it. Meanwhile, ‘Materials’ holds a substantial portion of the remaining interest, and its applications form a minor but still noteworthy portion of the research. There is compelling evidence that FRP can play a significant role in the development of concrete construction.

This survey illustrates that Elsevier is the leading publisher in “FRP in Concrete” related publications, owning 36% of the published papers. ASCE ranked 2nd by publishing 13.4% of the literature. In comparison, Springer contributed 6.7%, MDPI contributed 4.1%, ACI contributed

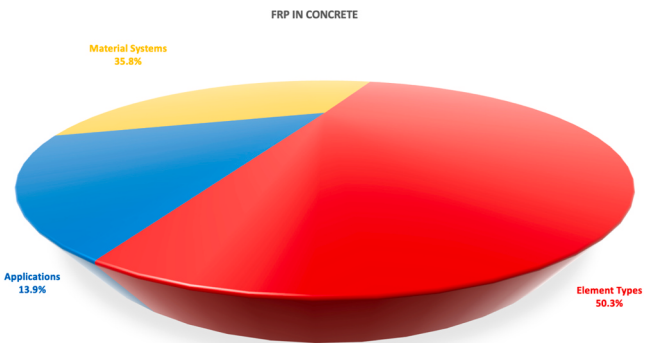


Fig. 13. Percentage of each category in FRP-related papers.

3.8%, Taylor and Francis contributed 3.5%, Trans Tech Publications Ltd 3.4%, SAGE contributed 2.6%, Techno-Press contributed 2.4%, and other outlets contributed 24% to the total publication. Overall, using FRP in constructing new concrete structures or rehabilitating existing structures offers many benefits over traditional materials, particularly regarding strength, durability, and long-term maintenance costs. These advantages must be weighed against the potential challenges of thermal expansion, fire resistance, bendability issues, and supply chain issues. Nonetheless, as technology continues to improve, the advantages of FRP are expected to become increasingly compelling, making it a more attractive material for concrete construction.

5. Conclusions and future work

FRP has been receiving increasing interest from researchers across various disciplines. Its unique properties, including its high strength-to-weight ratio, corrosion resistance, and design flexibility, present new opportunities for innovation. Additionally, as sustainability and efficient use of resources become more critical in our society, the potential for FRP to be used in place of heavier or corrosion-prone materials is high. The versatility of FRP makes it a compelling area of study with potential applications ranging from infrastructure and construction to aerospace and automotive industries. This paper provides an understanding of the historical trend in FRP in concrete-related publications, highlights the gaps in the field, and provides a summarized overview of the current literature. The following conclusions can be drawn from the publication analysis and the literature review:

- The publication of FRP-related papers increased from 1997 to 2022. The publication of FRP-related research in different fields of engineering, materials science, construction and building technology, etc., shows the variety and wide applications of this material.
- China and the United States have published the most FRP-concrete-related papers globally, with 1976 and 1448 papers, respectively. This higher number of publications can be attributed to the well-developed economies of these two countries, which enable them to provide more funding for research and development in this subject. Furthermore, the growing concern in the US regarding deteriorating infrastructures and the need to find a solution for future construction to avoid unnecessary repair and maintenance costs is likely another driving force in the development of FRP to reinforce and strengthen concrete structures in the US.
- The release of ACI 440.11–22 in September 2022 will affect the current trend in GFRP-related publications. It is expected that the rate of publishing in BFRP will increase significantly. More research is required to lay the foundation for including BFRP in the future version of the code. Since the current code covers the GFRP, many GFRP-related areas have previously been researched, and the material may be used in the construction with greater confidence. This, in turn, may reduce the publication rate in GFRP subjects but increase the rate of GFRP field deployment.
- The analysis revealed that a great amount of work was conducted to investigate the performance of FRP in concrete beams and columns, as seen in 83.4% of total published papers. This points to the need for published research in the areas of slab-on-ground and foundation footing, which prevent their inclusion in the current building code and widespread use in the construction sector. In addition, the non-structural slab-on-ground appears to be a low-hanging fruit to be researched, as numerous projects may benefit from FRP technology if sufficient literature is provided and reflected in the current code and guidelines.
- Despite the existence of a new building code for GFRP-RC elements, there is still room for research in areas not covered by the code, such as areas with limited published research. There is a lack of understanding and consensus among researchers such as seismic-force-resisting systems, fire resistance, deep beams, diaphragms, anchoring to concrete, shear transfer, shear friction, bundled reinforcement, strut models, tie models, shotcrete, hybrid construction, lightweight concrete, two-ways member contains GFRP bar, brackets, and corbels. Due to a lack of published research, related specifications, or an inadequate number of field implementations, these areas need to be covered in the current code. Exploring these topics will help to keep the GFRP-RC research alive and thriving.

CRedit authorship contribution statement

Nima Khodadadi: Writing – original draft, Visualization,

Validation, Methodology, Investigation, Data curation. **Hossein Roghani:** Writing – original draft, Investigation. **Ehsan Harati:** Writing – original draft, Investigation. **Mohammadamin Mirdarsoltany:** Writing – original draft, Investigation. **Francisco De Caso:** Writing – review & editing, Resources, Formal analysis, Conceptualization. **Antonio Nanni:** Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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