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Fiber-Reinforced Polymer Composites in Strengthening Reinforced Concrete Structures: A Critical Review

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ABSTRACT

Fiber-reinforced polymer (FRP) composites continue to provide designers with the ability to deliver innovative and intelligent solutions to overcome the ever-growing aging issues in infrastructure. Since it has been more than 50 years to the introduction of FRP materials to the construction industry, this paper presents a state-of-the-art review on historic and recent developments of FRP in strengthening and rehabilitation of civil engineering applications. This review highlights some of the classic and modern experimental, numerical, and analytical studies associated with the integration of FRPs into buildings, among other structures. The discussion presented herein aims at covering application of FRP systems in reinforced concrete structural members and also highlights the performance of FRPs (including bonding agents) under extreme conditions such as elevated temperature, saline environment, and cycles of freezing and thawing. This paper also presents a collective perspective on number of limitations, challenges and research needs associated with successful, sustainable, and durable implementation of FRPs in civil infrastructure.

Keywords: FRP; strengthening; concrete; seismic; fire; environmental exposure.

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1.0 INTRODUCTION

Fiber reinforced polymers (FRP) belong to a class of materials referred to as composites. Composites are manufactured by the combination of two or more constituent (parent) materials to form an enhanced compound with improved properties that are functionally superior to those of its parents [1-3]. In general, FRP materials comprise of high strength continuous fibers embedded in a polymer matrix (resin). The embedded fibers constitute of the main reinforcing elements, while the polymer matrix acts as a binder that protects fibers and facilitates transferring loads to-and-between these fibers.

There are three main types of fibers used in the construction industry that includes E-, S-, and Z-glass fibers, aramid fibers (aromatic polyamides, Kevlar 49) and carbon fibers (ultra-high modulus, high modulus and high-strength) [1-3]. The polymer matrices (resins), on the other hand, are classified into two groups, namely thermosetting or thermoplastics. The vinylesters, epoxies and polyesters are grouped under thermosetting matrices. Thermosetting matrices are crossed-linked polymers made either by addition or condensation polymerization. They are formed under the influence of heat and once formed they do not melt or soften upon reheating or dissolving in solvents. Thermosetting resins, which are more prominently used due to their improved mechanical performance, have better properties of impregnation and adhesion to fibers. Unlike thermosettings, thermoplastics such as polyethylene, polyvinyl chloride, polypropylene, and, polyurethane are more expensive to produce and very sensitive to surrounding environmental conditions.

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In general, resins can be made of polymers, metals, or ceramics. The polymer matrix is the most common material due to its easy process of manufacturing and relatively inexpensive production process. The combination of matrices with fibers have led to development of various classic FRP materials such as carbon FRP (CFRP), glass FRP (GFRP), aramid FRP (AFRP), basalt FRP (BFRP), and some newly-developed polythylene naphthalate (PEN) and polyethylene terephthalate (PET) composites [1-4]. Depending on the type of fiber and polymer matrix, the behavior of FRP materials can significantly vary, especially with regard to their mechanical properties. Figure 1 illustrates a comparison between stress-strain response curves of typical FRP materials.

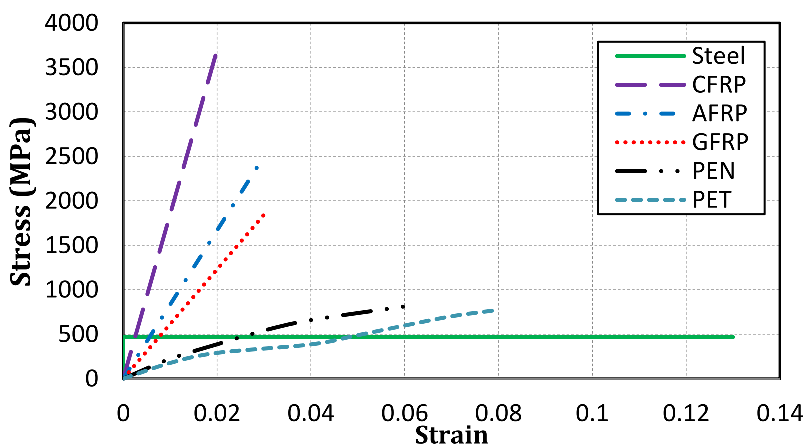

Fig. 1 Tensile stress-strain curves for structural steel and various FRP materials [1-4]

FRPs were originally introduced to aerospace, automotive and marine industries as low weight-to-high modulus and strength materials [1-3]. Due to their high cost and manufacturing complexities, FRPs were not practical for use in civil application but rather, unreinforced composites, which were cheaper to process, were utilized in non-structural applications as cladding and finishing materials. However, with the advancement of modern technology, FRPs have emerged as an attractive alternative for retrofitting and strengthening of concrete structures owing to number of advantages, they offer over traditional construction materials, such as concrete and steel [5].

Due to more recent improvements in properties of FRP materials such as corrosion resistance characteristics, environmental durability, and inherent tailorability, application of FRP continued to grow far beyond rehabilitation of existing buildings and into strengthening of large infrastructure and construction of new facilities, to some extent. For example, the applications of FRP materials range from retrofitting of reinforced and unreinforced masonry walls, seismic retrofitting of bridges and building, repair and strengthening of concrete structures, metallic and timber beams, girders, and slabs, and rehabilitation of unique structures such chimneys, historic monuments and off-shore platforms [1-3]. In recent years, the construction sector has become one of the world’s largest consumers of polymer composites [5-10].

In most of the above described applications, FRPs are primarily used as “externally bonded” systems to enhance flexural, shear, torsional, axial sectional capacity of reinforced concrete structural elements, and to provide additional confinement and improve stability and serviceability of structural members. In general, there are two main types of strengthening systems, the first employs FRP plates and/or sheets while the second utilizes near-surface mounted (NSM) bars. In the case of FRP plates and sheets, FRP products are applied to concrete surfaces only after

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preparing the external surface of concrete by grinding, sandblasting or high-pressure water jetting. This method of external strengthening is easy and quick to apply. It should be noted that although externally bonded steel systems were developed in early 1940s [11], to strengthen bridge girders, the introduction of FRP materials showed much improved performance mainly due to superior properties of FRP composites.

A closer look at aforementioned discussion infers that FRP-related applications are "bond critical" as they rely on bond action developed at the interface between FRP and concrete. Thus, one of the major drawbacks of applying FRP strengthening systems is the fact that FRP attachments may debond from the adjacent concrete surfaces. Debonding is known to occur at low axial strain level of FRP, thus externally bonded systems often do not utilize full tensile strength of FRP [1-3, 12]. In order to overcome such limitation, a relatively newer technique known as near-surface mounted (NSM) strengthening technique has been developed [12]. In this method, FRP strips or rebars are bonded into slits "grooves" cut into concrete cover using suitable adhesive (epoxy or grout). The adhesive in the groove ensures that FRP strip or rod is well-anchored to concrete to act as an effective tensile or shear reinforcement element. Compared to the other strengthening technique, NSM has been shown to better utilize bonded FRP materials [12-15].

Since concrete infrastructures are designed to last for several decades and to serve variety of users, these structures are subjected to varying load types and hazards [16-18]. Thus, researchers started investigating performance of FRP strengthening systems under unique load types including static (monotonic), cyclic (fatigue/seismic), impact, blast, and fire among others. This has led to

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development of advanced types of FRPs with much improved properties and versatile applications [19-22]. Some of the recently developed FRP systems include sprayed FRP systems [23], fire-resistant FRP material [24] and extra-ductile FRP products [4]. Aided by the growth in research around the world, the American Concrete Institute (ACI) published its first design guide, ACI 440.1R- 01, for FRP-reinforced concrete in 2001 [25] and been expanded and revised since then. Other design provisions were also developed and include International Federation for Structural Concrete (FIB) in 2001 [26], and Japanese code (BRI) in 1995 [27] etc. Due to the widespread of these codes, integration of FRP materials is now more natural (and frequent) in infrastructure construction projects [28-32].

The above review shows that applications of FRP materials have been rapidly growing which solidifies the fact that FRP materials continue to be an integral part of the modern construction industry. This study presents a state-of-the-art literature review on historic development and recent advancements of FRP composites in civil engineering applications. This study aims at highlighting some of the notable milestones, along with a number of studies associated with the integration of FRPs in strengthening concrete structures. The discussion presented herein intends on covering application of FRP strengthening systems in reinforced concrete structural members including, flexural, shear, torsional, axially and seismically loaded elements. In addition, the performance of FRP-strengthened concrete members under various environmental conditions is discussed. Then, a discussion on number of limitations, challenges and research needs associated with implementation of FRPs is presented.

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2.0 Types of FRP Strengthening Systems and Products

FRP materials are manufactured in a variety of products and are mainly categorized into two groups, constant cross-sectioned and pultruded sectioned. Constant cross-sectioned FRP composite structural shapes are often produced for use in construction industry, specifically in buildings and bridge applications, while pultruded sections are mainly used in highway bridge decks and pedestrians passes. In addition, FRP products can be further classified as those developed for use in new structures and those used for strengthening and retrofitting of existing structures. FRP reinforcements for new structures can be divided into three primary products: (1) FRP bars for use as internal reinforcement, (2) FRP tendons for prestressed concrete (PC) members, and (3) stay-in-place FRP formwork for reinforced concrete members [3].

The use of FRP materials to strengthen and/or repair load-bearing structural elements in existing structures is referred to as "retrofitting". Retrofitting applications can be broadly classified into two types. The first type is called "strengthening", where structure's initial strength or ductility need to be upgraded to account for new services or levels of loading. This increase may be necessitated by the desire to make the structure compatible with existing building regulations or may be desired due to changes in intended use of the structure. The other type of FRP retrofitting can be classified as "repairing". In the latter case, FRPs are used to repair an existing and deteriorated structure to bring its load-carrying capacity, ductility or stability back to the level for which it was designed for.

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In any way, the most commonly used FRP products are manufactured as prefabricated plates, bars, sheets and anchorages. The mechanical properties of different types of FRP composite materials [1-4, 33-37] that are used in the construction market are provided in Table 1. It should be noted that prefabricated FRP elements are typically stiff and is difficult to bend or use as internal reinforcement (stirrups). FRP fabric, on the other hand, is available in continuous uni-or bi-directional sheets supplied that can be easily tailored to fit any geometry and wrapped around complex profiles. FRP fabrics may be adhered to the tension side of structural members (e.g. slabs or beams) to provide additional tension reinforcement to increase flexural strength, wrapped around the webs of joists and beams to increase their shear strength, and wrapped around columns to increase their shear and axial strength and improve ductility and energy dissipation characteristics.

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Table 1 Properties of typical commercially produced FRP products [1-4, 33-37]

	FRP Plates/Strips					
	Standard Modulus Carbon reinforced	**High-Modulus Carbon reinforced**	**GFRP**	**Carbon reinforced Vinylester**	**Hybrid FRP plate**	**BFRP**
Fiber volume	65-70	65-70	65-70	60	NA	68.7
Fiber architecture	Unidirectional	Unidirectional	Unidirectional	Unidirectional	Unidirectional	Unidirectional
Thickness (mm)	1.2-1.9	1.2	1.4-1.9	2	3.65	1.27
Tensile strength (MPa)	2690-2800	1290	900	2070	376	1417
Tensile modulus (GPa)	155-165	300	41	131	24.4	59.2
	FRP Bars					
	Glass reinforced Vinylester (13 mm diam.)	**Glass reinforced Vinylester (25 mm diam.)**	**Carbon reinforced Vinylester (13 mm diam.)**	**Carbon reinforced Vinylester (13 mm diam.)**	**AFRP (38 mm diam.)[**]**	**BFRP (18 mm) [***]**
Fiber volume	50-60	50-60	50-60	50-60	NA	NA
Fiber architecture	Unidirectional	Unidirectional	Unidirectional	Unidirectional	Unidirectional	Unidirectional
Tensile strength (MPa)	620-690	551	2070	2255	1448	676
Tensile modulus (GPa)	41-42	41	124	145	70.3	35.2
	FRP Sheets and Fabrics					
	Standard Modulus Carbon Fiber Tow Sheet	**High Modulus Carbon Fiber Tow Sheet**	**Glass fiber (Unidirectional)**	**Basalt fiber[*] (Unidirectional)**	**PET900 (Unidirectional)**	**PEN900 (Unidirectional)**
Fiber architecture	Unidirectional	Unidirectional	Unidirectional	Bidirectional	Unidirectional	Unidirectional
Thickness (mm)	0.165-0.330	0.165	0.356	0.17	1.262	1.273
Fiber tensile strength (MPa)	3790	3520	1520-3240	2100	740	790
Tensile modulus (GPa)	230	370	72	91	10	15
Strain at rupture (%)	1.2-1.5	1.0-1.5	3.5	2.4	7	5

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3.0 Types of FRP Strengthening Applications in Reinforced Concrete Structures

In the last three decades, the integration of FRP strengthening systems has been increased due to the superior characteristics of these composites. This has been duly noted in the open literature by the amount of research and published work. This section aims at highlighting some of the notable experimental, numerical and analytical investigations carried out in recent years. In particular, studies related to flexural, shear, torsional, axial and seismic strengthening are presented.

3.1 Flexural applications

The flexural capacity of plain and reinforced concrete (RC) elements can be enhanced through attaching externally bonded FRP plates, strips or fabrics at the soffit of simply-supported beams (see Fig. 2). Several failure modes were experimentally observed of RC beams and slabs when externally strengthened with FRP laminates. According to the current ACI 440.2R-08 [38] design guidelines, steel yielding followed by rupture of FRP laminates, FRP debonding from adjacent concrete surface, and concrete cover separation (cover delamination) are common failure modes of strengthened RC members in flexure with FRP laminates. Rupture of the externally bonded FRP laminate will occur if the strain in the FRP reaches its ultimate strain, before the concrete in the top compression fiber reaches its crushing strain. FRP debonding or cover delamination usually occurs if the axial force in the flexural FRP reinforcement cannot be sustained by the concrete substrate. Debonding of FRP laminates is usually initiated by flexural and/or flexural-shear cracks in the vicinity of maximum moment region of strengthened member and then progress along the length of FRP through the bonding agent (epoxy adhesive or cement

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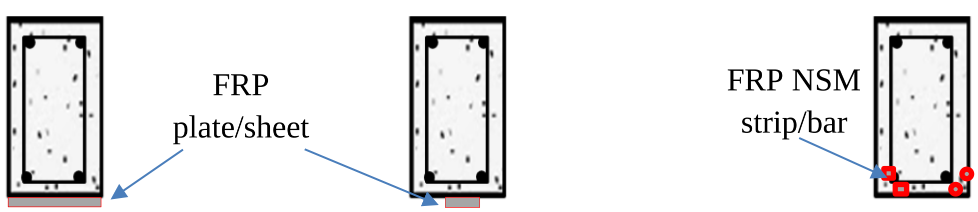
matrix). Such cracks open and widen under loading and will thus develop high levels of shear stress at the interface between the FRP sheets/plate and concrete substrate, causing FRP debonding. Concrete cover separation (cover delamination) is another type of the debonding brittle failure mode that is usually initiated by the formation of a crack at the high stress concentration point close to the end (curtailment) of FRP laminate. The crack will then propagate to and along the level of flexural steel reinforcement, causing the separation of concrete cover. Failure of the concrete cover is initiated by the formation of a crack near the plate end. The crack propagates to and then along the level of the steel tension reinforcement, resulting in the separation of the concrete cover layer from the rest of RC beam or slab. The potential failure modes of externally strengthened RC flexural members with FRP laminates are shown in Fig. 3.

(a) Typical RC beam



(b) Various FRP schemes

Fig. 2 Illustration of use of FRP for flexural strengthening in RC beams (FRP size is slightly exaggerated for illustration purposes)

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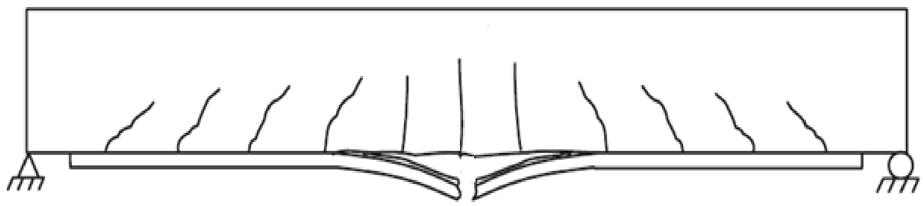
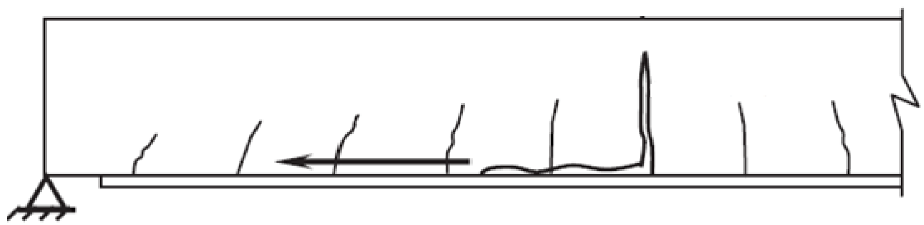
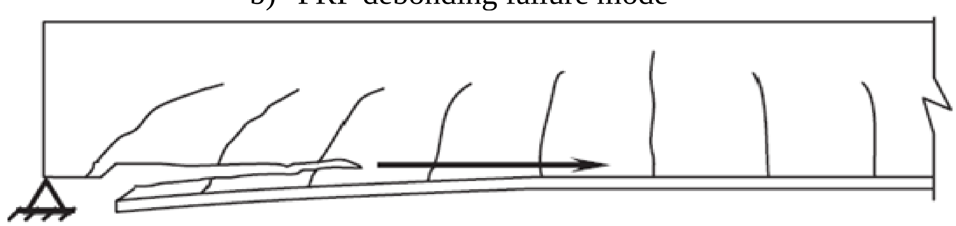


a) FRP rupture failure mode



b) FRP debonding failure mode



c) Concrete cover separation failure mode

Fig. 3 Conventional failure modes of externally strengthened reinforced concrete members with FRP laminates

Alternatively, near-surface mounted strips (NSM) or rods with fiber direction parallel to the member longitudinal axis can also be utilized [9, 37]. This use of externally bonded plates and NSM CFRP systems to strengthen RC beams in flexure has been well studied over the past three decades [1-3] and some of these studies are highlighted herein. In an early study by Ritchi et al. [39] in 1991, strengthened RC beams with adhesively bonded GFRP and CFRP plates were tested to failure. The tested beams were 2.75 m long and were subjected to dominant flexural effects. Results of this investigation revealed that strengthened beams achieved 17 to 95% increase in

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stiffness, and 40-97% increase of ultimate strength when compared to similar unstrengthened control beams.

In another study, Meier et al. [40] carried out experiments on 60 small-scale RC beams tested in a four-point bending set-up. These beams were strengthened using CFRP sheets that are 0.3 mm thick and 200 mm wide. The test outcomes of these tests have shown that the flexural capacity of strengthened beams have significantly increased over that of an unstrengthened beam specimen up to 100%. Arduini and Nanni [41] also carried out tests in which they strengthened pre-cracked RC beams with CFRP sheets. Arduini and Nanni reported that carbon fiber stiffness, fiber direction, and number of plies can significantly affect the performance of strengthened beams. For instance, wrapping of FRP sheets perpendicular to edges of strengthened beam (and on top of longitudinally applied FRP sheets) can be effective in anchoring bonded CFRP sheets and delays debonding of FRP strengthening system.

In order to investigate the effect of number layers of bonded FRP sheets, Toutanji et al. [42] tested seven RC beams externally strengthened with three to six layers of CFRP sheets. Their results indicated a significant increase in the load–carrying capacity up to 170.2% of the unstrengthened control beam. Toutanji et al. observed that not only ductility of strengthened beams tends to significantly reduce with the increase of number of bonded sheets, but failure mode of strengthened specimens also changes. For example, beam specimens strengthened with three and four layers of CFRP sheets failed by rupture of FRP, while specimens strengthened with five and six layers of CFRP sheets failed by concrete cover delamination. Fanning and Kelly [43] presented, in a similar experimental program, the results of ten RC beams strengthened with different plate length configurations. Similar studies that investigated the effect of FRP attachment length were also carried out by Al-Tamimi et al. [44], and Xiong et al. [45]. Those studies concluded that effectiveness of strengthening is significantly reduced when CFRP plate lengths were shortened.

Most of the above studies showed that bonding CFRP sheets or plates significantly increases ultimate strengths of strengthened beams, while use of GFRP strengthening materials increases beams' ductility. Thus, in order to develop an optimum solution, number of researchers have investigated the effect of using hybrid combination of FRP materials. One such investigation was carried out by Xiong et al. [45]. These researchers conducted a test program on the behavior of two strengthening systems namely; a conventional CFRP system as well as a hybrid CFRP/GFRP system. It was observed that beams strengthened with hybrid combination of CFRP and GFRP sheets showed an increase of 89.7% in the deflection response over that of CFRP-strengthened beams. It was also observed that the ductility of the RC strengthened beam using the hybrid system was only 16.2% less than that of the control "unstrengthened" beam.

Hawileh et al. [46] also carried out an experimental and an analytical investigation of the behavior of RC beams strengthened by means of different combinations of externally bonded hybrid GFRP and CFRP sheets. Hawileh et al. observed that depending on the combination of the CFRP/GFRP sheets, the increase in the load bearing capacity of the strengthened beams ranged from 30% to 98% of the unstrengthened beam. They also reported that the ductility of beams strengthened with glass and hybrid sheets is higher than that with CFRP sheets. Wu et al. [47]

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studied the effect of hybrid FRP sheets through combining high strength and high modulus carbon sheets to form a new hybrid system which they tested on fifteen pre-cracked RC beams. These beams were tested under three points bending to failure. The outcome of these tests has shown that the optimum hybrid combination is using a high strength to high modulus ratio of 2 to 1.

Although most of the above discussed investigations were carried out on simply-supported beams, the open literature also has number of experimental investigations carried out on continuous beams [48] and others with fixed end supports [49]. In more recent studies, Akbarzadeh and Maghsoudi [48] experimentally investigated the performance of continuous high-strength RC beams externally strengthened with CFRP and GFRP sheets. They concluded that as the number of CFRP sheets increases, the load–carrying capacity of the tested specimens increases and moment redistribution and ductility decrease along with a decrease in the CFRP ultimate strain at failure. Similarly, for the specimens strengthened with GFRP sheets, test results showed that by increasing the number of GFRP sheets, the moment redistribution and ductility would decrease without a significant increase in the load–carrying capacity. Similar tests were also carried out by Tajaddini et al. [49] and El-Refaie et al. [50].

As discussed earlier, number of experimental tests had showed that NSM rods/strips can be successively applied in strengthening or upgrading RC members in flexure. For instance, Badawi [51] conducted an experimental program on twenty two RC beams to investigate the monotonic and cyclic behavior of conventional and prestressed NSM strengthened concrete members. The outcome of his tests has shown that ultimate strength can significantly increase by

26-91% in case of conventional and prestressed NSM rebars. Hassan and Rizkalla [52], EL-Hacha and Rizkalla [53] also carried out similar experimental programs and have reported similar results to that of Badawi [51].

Similar to RC beams, several studies were carried out to investigate the viability of using FRP materials to strengthen RC slabs and slab-like members. For example, Yao et al. [54] tested eighteen FRP-strengthened RC slabs. Outcome of these tests showed an increase in flexural capacity of strengthened slabs. Similarly, Teng et al. [55] also tested ten cantilever slabs bonded with GFRP strips. Although strengthened slabs achieved higher flexural capacity, all GFRP strengthened slabs were found to experience debonding of FRP strips from the slab which triggered failure through complete debonding or FRP tensile rupture. Other experimental tests were carried out by Smith et al. [56]. Smith et al. reported results of tests on ten FRP-strengthened RC slabs anchored with FRP anchors of various shapes and positioning. These tests have shown an enhanced flexural capacity in the range of 44% to 216%, respectively.

In a separate study, Dalfré et al. [57] carried out tests on seventeen statically indeterminate (continuous) reinforced concrete (RC) slabs strengthened with NSM-CFRP laminates. The test program investigated the effect of strengthening both hogging and sagging regions of slabs. The obtained results showed that the CFRP-NSM strengthening technique significantly increased load carrying capacity of tested slabs, even for those with relatively high steel reinforcement ratios. El-Maaddawy et al. [58] also presented test results of eleven continuous RC slab strips with cut-offs. Eight of these slabs were strengthened in flexure using NSM reinforcement. On a similar note, El-

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Maaddawy et al. showed that NSM strengthening can fully restore original strength with cut-offs. The strength gain, in these tests, was more pronounced for specimens strengthened in the deficient sagging region.

In parallel with conducting experimental tests, numerous researchers used finite element (FE) to model and study the flexure and shear behavior of RC beams strengthened with externally bonded and near surface mounted FRP bars, sheets and laminates as well as other strengthening materials [59-71]. Most researchers used general purpose FE programs with some modifications to analyze RC beams and slabs strengthened with FRP composite materials. One of the first numerical studies was carried out by Kachlakev et al. in 2001 [72]. In this study, the authors laid out principles, simulation techniques and input parameters required to accurately simulate FRP-strengthened concrete structures. While this study provided a framework for simulating FRP plates attached to soffit of RC beams, it did not present any techniques or recommendation to account for bond action between FRP and concrete, perhaps due to the lack of numerical representations (i.e. elements, constitutive models, etc.) needed to numerically simulate bond behavior at that time. This issue was further addressed in recent studies [73-76].

Three-dimensional (3D) FE modeling of RC beams externally strengthened with FRP plates or sheets are usually developed by discretizing the 3D geometry into finite elements to model the concrete, steel reinforcement, supports, and FRP laminates, respectively. Quarter models of tested specimens could be developed if there is symmetry in geometry, material properties, boundary conditions, and loading. The major advantage of developing quarter FE models if applicable is the tremendous reduction in computational time [76]. Symmetry is usually

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simulating by applying rollers perpendicular to the plane of symmetry. Figure 4 shows representative samples of typical 3D models of control unstrengthened and externally strengthened RC beams in flexure with FRP laminates [76].

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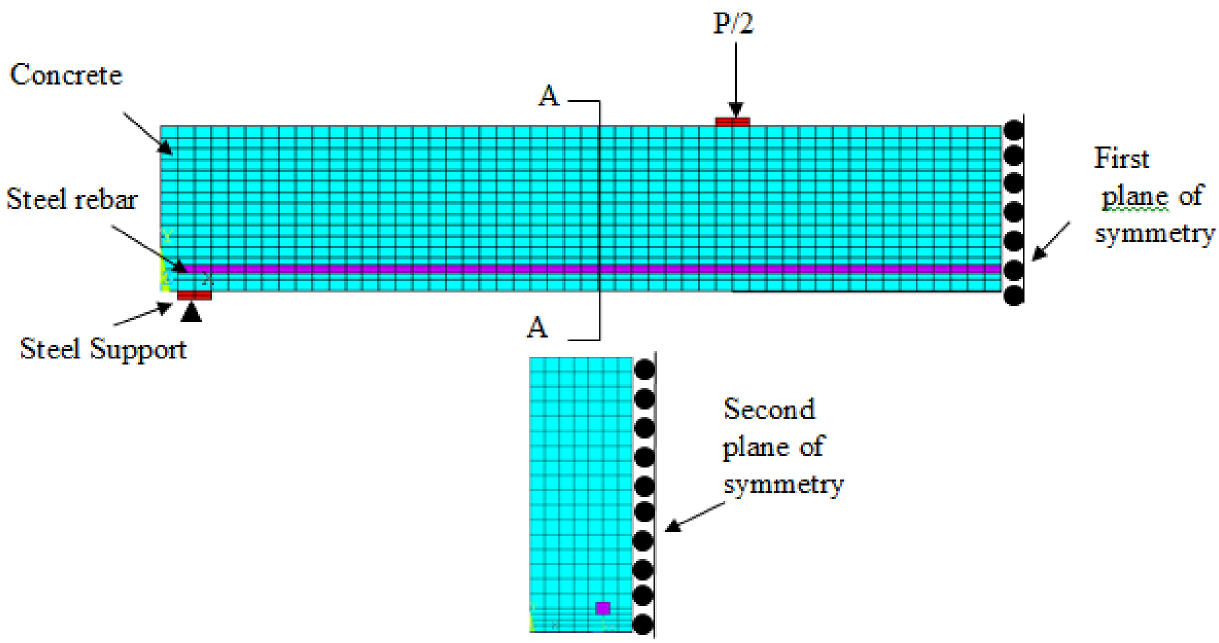
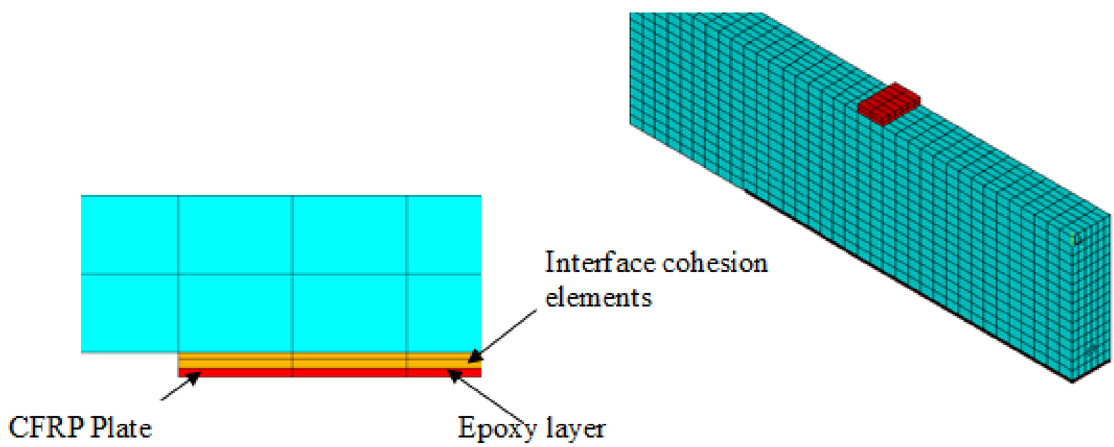


a) Control unstrengthened reinforced concrete beam



b) Strengthened reinforced concrete beam in flexure with CFRP plate

Fig. 4 Typical detailing of unstrengthened and strengthened reinforced concrete beams with FRP laminates [76]

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The concrete material shown in Fig. 4 is modeled using 3D brick elements, having 8 nodes per element. Each node is defined with three translational degrees of freedom. The concrete brick elements have the capability of cracking in tension and crushing in compression. The steel reinforcement is usually modeled using 3D spar elements. Each spar element is defined by two nodes, each of which has three translational degrees of freedom as well. The spar element should be capable of yielding in tension and compression and thus deforming in the elastic and plastic ranges. The FRP plate or sheet shown in Fig. 4 is usually modeled using shell elements [76] with orthotropic material properties. A small layer of epoxy layer could be also added to the developed FE model using brick elements to simulate the bond layer between the CFRP and concrete interface as shown in Fig. 4(b). I addition, the loading and restraining supports are modeled 3D brick elements with rigid steel material properties as shown in Fig. 4. Simulating the loading supports with brick elements would prevent any major stress concentration on concrete elements under the applied concentrated loading locations [76]. It is also usually assumed perfect bond between the steel reinforcement and concrete and between the concrete material and FRP laminates. However, in this study [76], bond-slip behavior between the concrete and steel reinforcement is simulated using spring elements. In addition, cohesion interfacial elements are used to simulate the bond between the FRP plate/sheet and adjacent concrete surfaces [76]. Those cohesion 3-D 8-node linear interfacial elements are capable of simulating different interfaces between two surfaces as well as the delamination process. Debonding is initiated when coincident nodes are subjected to increasing longitudinal or transverse displacement. Loading is usually simulated by applying vertical displacement to the loading support to capture the plastic deformation of the tested specimens. More information about FE modeling techniques of strengthened RC flexural members in terms of geometry, element types, material properties, bond-slip models, loading and boundary conditions, and failure criteria could be found in the work published by Hawileh et al. [76].

Lu et al. [73] also developed a meso-scale FE model to predict the debonding process in FRP-concrete bonded joints using a fixed angle crack model. However, this model was used to simulate bonded concrete joints (prisms) and was not tested against full scale RC members. Chen et al. [74] investigated the effects of various modeling assumptions on the interfaces between concrete, steel reinforcement and shear stirrups, as well as between concrete and FRP plate. In order to capture bond behavior, Chen et al. used interfacial elements to model the bond between FRP and concrete interfaces. These authors have also reported the importance of modeling the bond behavior between steel reinforcement, concrete and FRP in achieving good correlation with the measured experimental results. Hawileh et al. [15, 75] developed 3D nonlinear FE models that used a combination of spring and cohesive elements to predict debonding phenomenon of different platted and NSM strengthening systems. The implementation of such technique has shown good correlation against experimental tests.

Furthermore, Sasmal et al. [66] used a general purpose FE program to carry out nonlinear analysis of parent and FRP strengthened reinforced concrete (RC) beams. Zhang et al. [67] presented FE approach for predicting end cover separation failures in RC beams strengthened in flexure with either externally bonded or near-surface mounted (NSM) FRP reinforcement. The proposed FE approach provided accurate predictions of experimental results, including load–deflection curves, failure loads and crack patterns. Barbato [70] presented a new simple and efficient two-dimensional (2D) frame FE to estimate the load-carrying capacity of RC beams strengthened in flexure with externally bonded FRP strips and plates. The predicted load-carrying capacity and the load-deflection response of RC beams agreed closely with experimental results. Furthermore, Anil et al [61] investigated the behavior of RC beams, retrofitted with CFRP strips and with and without anchorages, using nonlinear 3D FE analyses. They modeled eight beams with varying cross sectional properties, and they studied the effect of CFRP strip width, presence of fan-type anchorages, and CFRP patches as main variables. From the results, they concluded that FE simulations are efficient tools for predicting the nonlinear behavior of CFRP-retrofitted RC beams.

Teng et al. [77] also developed a three-dimensional meso-scale finite element model to study the bonded joints between a near-surface mounted FRP strip and concrete. The FRP and the adhesive were modeled as linear brittle-cracking materials and the local bond stress distributions and the bond-slip relationships were extracted and analyzed. Chen et al. [78] also developed a FE model for investigating debonding failures in FRP-strengthened RC beams using a dynamic approach. The proposed model provided accurate predictions of experimental results. Table 2 provides a detailed list of number of other experimental programs carried out recently on beams and slabs.

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Table 2 List of selected experimental studies carried out on FRP-flexurally strengthened RC beams

Researchers	Year	FRP material type	Strengthening system	Program details and Main findings
Norris et al. [79]	1997	CFRP	Sheets	Nineteen pre-cracked concrete beams were tested to failure. Results indicate that the increase in flexural capacity, stiffness and failure mode depends on the direction and orientation of attached CFRP sheets. This increase in flexural capacity was quantified to be in the range of 50-75%.
Grace et al. [80]	1999	CFRP/GFRP	Sheets	Fourteen simply supported beams were strengthened with various FRP configurations and tested. It was observed that the use of FRP sheets reduced cracks and deflections as well as increased load carrying capacity in strengthened beams. Vertical FRP sheets also prevented rupture of flexural FRP sheets. In general, the ultimate load carrying capacity can be doubled by using a proper combination of horizontal and vertical fibers.
Hassan and Rizkalla [52]	2002	CFRP	NSM rebars/sheets	Half-scale models of CFRP-strengthened prestressed concrete beams were tested. In these tests, both stiffness and strength of strengthened RC beams were increased by 50%. The magnitude of strength increase was influenced by the type and configuration of the CFRP rebars/sheets. This study also compared the economical aspect of various FRP systems through showing that the overall cost of using CFRP sheets was cheaper (by about 25%) than that using NSM rebars.
Limam et al. [81]	2003	CFRP	Strips	Two two-way slabs strengthened with CFRP strips were tested to failure. The ultimate load capacity of the strengthened slab was about 2.5 higher than that of the unstrengthened slab. Still, the unstrengthened slab underwent a more ductile response than the strengthened slab probably due to the premature debonding of CFRP strips during the test. Limam et al. also developed an analytical model that incorporates diagonal yield lines and associated collapse mechanism.
Ceroni et al. [82]	2010	CFRP	NSM/Plates	Flexural tests were carried out on 21 RC beams strengthened with a combination of NSM bars and CFRP plates. The outcomes of these experiments illustrated the efficiency of FRP when externally bonded as sheets and/or NSM rebars. In beams strengthened with CFRP sheets, the increase in failure load varied between 17% and 50% depending on the ratio of steel reinforcement, unfortunately this increase was also accompanied with a noticeable decrease in ductility. On the other hand, using an NSM system has enhanced both ultimate load capacity and ductility (by 46–72%). Ceroni et al. noted that it is possible for beams strengthened with CFRP sheets to achieve adequate ductility by utilizing U-sheets.
Anil et al. [83]	2013	CFRP	Strips	Twelve one-way FRP-strengthened reinforced concrete slabs were tested under four point loading set-up. Outcome of these tests showed that the average increase in load carrying capacity and stiffness were in the range of 1.16-1.48 and 1.05-1.22, respectively, of the unstrengthened slab. Anil et al. also noted that due to high elasticity of CFRP material, strengthened slabs underwent high reductions in energy dissipation capacity and ductility ratios.
El-Gamal et al. [84]	2016	CFRP/GFRP	Hybrid (sheets and NSM)	Ten full scale RC beams were casted and strengthened in flexure with different FRP materials. All strengthened beams showed increase in flexural capacity of about 31-133%. The CFRP strengthened beams achieved higher ultimate loads than those strengthened with GFRP sheets while GFRP strengthened beams, underwent a more ductile behavior. Outcome of tests was shown to be in good agreement with predictions from ACI 440 codal provisions.

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Fu et al. [85]	2017	CFRP	Plates/Sheets	A total of eight FRP-plated RC beams were tested with or without FRP U-wraps. Test observations have shown that using horizontal FRP sheets to anchor FRP soffit plate led to 10% increase in failure load. Results also showed that while using inclined FRP U-wraps in high moment region can lead to a significant increase in utilizing tensile strength of FRP soffit plate, using similar wraps installed in the low moment region can both suppress debonding and significantly increase both ultimate load and ductility up to 98.3% of that achieved by a control beam.

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3.2 Shear applications

FRP, as a strengthening material, has also been used to enhance shear capacity of RC beams. In such application, FRP strengthening systems can be used in variety of techniques including side bonding of FRP sheets and/or plates in addition to use of NSM technique (see Fig. 5). In the case of side bonding of FRP, individual and relatively narrow sheets/plate are bonded and spaced at external sides of the RC beam to act in parallel in resisting shear forces, similar to internal steel stirrups. One of the early studies that investigated shear response of FRP-sided bonded RC beams was conducted by Chajes et al. [86]. Chajes et al. carried out experimental tests on a series of twelve under-reinforced concrete T-beams to study the effectiveness of using externally applied composite fabrics in increasing shear capacity. These researchers used woven composite fabrics made of aramid, E-glass, and graphite fibers bonded to the web of the T-beams. The outcomes of the conducted tests inferred that shear capacity in strengthened beams can increase up to150% over unstrengthened specimens.

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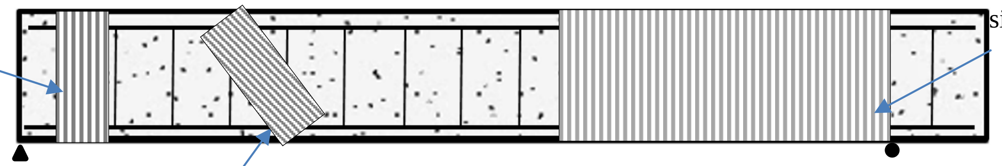
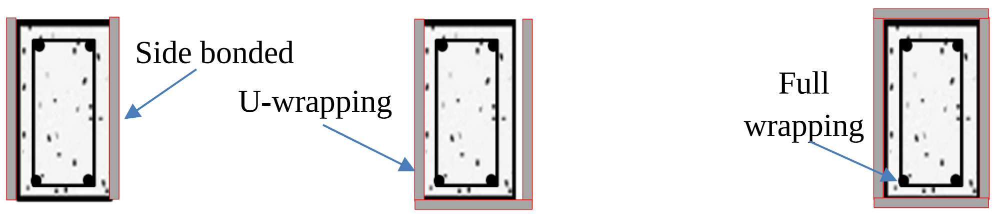


(a) Typical FRP strengthened RC beam



(b) Various FRP schemes

Fig. 5 Illustration of use of FRP for shear strengthening in RC beams

Findings of that study triggered investigation on the use of much wider FRP sheets covering both sides and soffit of RC beams in what is referred to as "U-wrapping". Carolin and Taljsten [87] and El-Maaddawy and Chekfeh [88] showed that shear strength of RC beams was restored through CFRP shear strengthening. These researchers and others [89-90] also reported that the use of proper end anchors delayed or prevented CFRP debonding which significantly increased the shear strength gain. In a more recent study, Chennareddy and Taha [91] have shown that combining NSM and U-wrapping of RC beams can significantly enhance the shear and flexural capacity. However, adopting such hybrid strengthening system, have resulted in changing the failure mode of tested beam from debonding of NSM bars to abrupt failure caused by rupture of NSM-FRP bars.

When it comes to the behavior of solid RC deep beams strengthened with FRP composites, this topic has received little attention in the literature [92-94]. Islam et al. [92] reported up to 40%

enhancement in the shear strength of deep beams due to the use of externally bonded CFRP system. Unlike the study by Zhang et al. [93] which indicated that CFRP shear strengthening of deep beams resulted in about 46% increase in shear capacity. Unfortunately, there is not enough information on the behavior of RC deep beams with "cut-off" or openings strengthened in shear with FRP composites. One of the few experimental tests published in the literature was by El-Maaddawy and Sherif [94]. They demonstrated the effectiveness of using CFRP shear strengthening around web openings to upgrade shear capacity. El-Maaddawy and Sherif also reported a shear strength gain in the range of 35–73%. These tests were then further examined by means of FE simulation in a companion study by Hawileh et al. [95]. Results of that numerical study echoed recommendations by a comprehensive review study by Ahmed et al. [96] to conduct further research to better understand the behavior of RC beams containing openings strengthened with externally bonded FRP materials.

The viability of using externally bonded CFRP composite systems to improve the shear behavior of shallow RC beams containing openings was also briefly reported in the literature by few researchers [97, 98]. For example, Pimanmas [97] indicated that the use of inclined NSM composite rebars externally installed diagonally to the beam's axis alongside the opening cut-off, and throughout the entire beam depth, can fully restore shear capacity of RC beams with web openings. El-Maaddawy and El-Ariss [98] reported that attaching CFRP sheets around the opening could positively improve both shear capacity and overall beam's stiffness. They also observed that doubling the amount of vertical CFRP sheets from one to two layers increased the shear capacity, but the additional shear capacity gain was not in linear proportion to the added

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amount of CFRP reinforcement. An analytical approach for prediction of the shear capacity of RC beams with openings strengthened in shear with CFRP laminates was also introduced based on the ACI 440.2R-08 design philosophy [38].

The above studies have shown that shear strengthening of RC beams has been achieved through bonding FRP plates or sheets to the beam’s sides. However, in practical conditions, beam sides may not always be accessible for strengthening upgrades due to accessibility limitations, unique geometry, etc. In order to overcome such challenges, few researchers have investigated the contribution of FRP flexural reinforcement on the shear strength of RC beams [99-101]. One of these researchers was Sobuz et al. [99] who tested four flexurally deficient beams strengthened with one, two, and three layers of CFRP laminates bonded to the tension side of the beam (bottom soffit). All specimens were tested under four-point bending, and those strengthened specimens showed an improved flexural capacity by 54–85% over the control unstrengthened beam. Nawaz et al. [100] also carried out similar experimental and analytical investigation. In their tests, strengthened beams showed a 13 to 138% increase in shear capacity due to installing thin FRP sheets along the soffit of the beams. It should be noted that there is large number of studies carried out recently to investigate various factors influencing shear strengthening of RC beams such as inclined bonded sheets, FRP material types, and loading set up. Some of these studies are summarized in Table 3. Several researchers also used finite element method to model and study the behavior of the shear deficient beams strengthened with externally bonded FRP sheets and laminates [64, 68, 69]. Haddad et al. [64] used nonlinear FE to investigate the performance of heat-damaged and shear-deficient beams, retrofitted with NSM and CFRP strips. Zomorodian et al. [68]

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developed a FE model by modifying the RC softened membrane model to predict the shear behavior of FRP-strengthened RC members. The developed model was validated by predicting the monotonic responses of 10 FRP strengthened RC panels subjected to pure shear stresses. There was good agreement between the experimental and analytical results. Godat et al [69] use different model simulate and assess the behavior of RC beams strengthened in shear using externally bonded FRP laminates. They used three different types of interface element, which significantly influenced the numerical predictions of FRP shear-strengthened beams.

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Table 3 List of selected experiments carried out on FRP-shear strengthening of RC beams

Researchers	Year	FRP material type	Strengthening system	Program details and Main findings
Triantafillou [102]	1998	CFRP	Sheets	Eleven RC beams strengthened in shear with CFRP sheets at various area fractions and fiber configurations were tested. These tests have shown that effectiveness of vertically attached FRP sheets increases linearly with axial rigidity of FRP until it reaches a maximum level beyond which the positive contribution of FRP diminishes. It was also noted that CFRP sheets used for shear strengthening rupture at stress levels below their ultimate strength due to stress concentrations in the sheet and this observation was the basis for an early model to quantify contribution of FRP to shear capacity.
Triantafillou, [103]	2000	FRP	Sheets/Plates	Presented a simple design model for the calculation of the fiber-reinforced polymer (FRP) contribution to the shear capacity of strengthened RC beams. The proposed model, which improves earlier work performed by Triantafillou [103], calculates FRP contribution in an analogy similar to that of steel stirrups. This model was calibrated and validated using 75 tests.
Micelli et al. [104]	2001	CFRP/AFRP	Sheets	Twelve RC T-joists strengthened with FRP composites were loaded until failure in a short shear span configuration. In these tests, all strengthened beams showed moderately improved performance in terms of ultimate strength capacity and flexural stiffness. The minimum observed gain in terms of capacity was in the range of 12-39% for a single U-wrap member without and with end anchorage, respectively. These tests have also shown that increasing the amount of CFRP reinforcement (number of sheets) may not result in a proportional increase in the shear strength unless debonding is delayed through using end anchors.
Zhang et al. [93]	2004	CFRP	Sheets/Strips	Sixteen deep beams without steel shear reinforcement were tested. Presented tests showed that using diagonal side strips angled at 45 and 135° yield improved performance than using vertically sided (90°) sheets in arresting shear crack propagation. Diagonally sided sheets significantly improved ultimate shear strength and ductility (by 31-80%).
Sobuz et al. [99]	2011	CFRP	Sheets	Sobuz et al. tested four flexurally deficient beams strengthened with varying number of FRP layers. Tests outcome showed that longitudinally bonded CFRP sheets can increase cracking load of CFRP strengthened beams with 1, 2 and 3-layers by 25%, 50% and 75%, respectively, whereas the percentage increase of ultimate load are 54%, 73% and 85%.
El-Maaddawy [98]	2012	CFRP	Sheets	Sixteen RC beams with various web opening size and locations were strengthened in shear with externally bonded CFRP sheets. Tests results indicated that CFRP shear strengthening around the openings of RC deep beams increased shear strength and overall stiffness. The shear strength gain caused by CFRP sheets was in the range of 66–71% when the opening was located at the mid-point of the shear span.
Akroush et al. [105]	2017	CFRP	Sheets	Eight continuous RC beams strengthened with CFRP sheets were tested in shear. Outcome of these tests showed that using CFRP sheets increased cracking strength (i.e. when shear crack initiates) by 21–47% as compared to that of the unstrengthened beam. Analysis of test

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	results also showed that post-cracking shear strength for all the strengthened beams also improved by 37-62%. Tests carried out by Akroush et al. [105] reported a slight difference of 4–6% from ACI 440 predictions which implies adequacy of codal provisions.

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3.3 Torsion applications

FRP as external reinforcing materials and systems are often extensively used to enhance the strength requirement related to flexure and shear in RC beams and column. But strengthening of members subjected to torsion is the least researched area as can be seen by the limited number of published studies. This is due to the fact that beams are mainly subjected to flexural and shear effects, and most codal provisions tend to neglect effects of torsion when beams have sufficient shear reinforcement [106]. Further, the complicated test set-up required to carry out torsional tests is another challenge that hinder such research efforts. In general, torsional strengthening of beams follows that of flexure and shear strengthening, in which beams continue to be strengthened with conventional FRP sheets, plates and/or NSM strips. Up to the authors' knowledge, the use of hybrid strengthening systems or use of ductile FRP materials (such as PEN and PET fibers) in torsional application is not fully investigated yet. Typical strengthening schemes used in torsional application are very similar to those used in shear strengthening (see Fig. 3).

Among the limited research studies published in this field, Salom et al. [107] carried out an experimental and analytical program to address torsional behavior of six fully wrapped strengthened spandrel beams by CFRP composites. Results from these tests have inferred that all six beams achieved 50% increase in overall ultimate torsional strength but suffered from general FRP debonding combined with excessive concrete crushing. Khalaf and Bayer [108] conducted another series of experimental tests to measure torsional effectiveness of externally bonded CFRP sheets to RC beams. Two types of wrapping were used, fully and partially wrapped sheets. In these tests, fully wrapped beams achieved twice the ultimate torque with respect to the reference (unstrengthened) beam. The fully wrapped beams also provided better confinement conditions which substantially improved concrete strength and prevented crack widening. Khalaf and Bayer also noted that sufficient anchorage in the U-jacket sheets improved the overall response significantly.

Mohammadizadeh and Fadaee [109] also conducted an experimental study on strengthening RC beams with high strength concrete (HSC). In this study, seven beams were tested, and CFRP sheets were used for strengthening purposes. These tests have shown that all strengthened beams exhibited an increase in both cracking and yield torque strengths depending on the strengthening configuration and amount of added CFRP reinforcement. The authors reported that using anchors in U-wrapped beams avoided CFRP delamination and achieved identical torsional capacity as compared to a full wrapped beam with one-layer CFRP sheet. On the other hand, Al-Bayati et al. [110] investigated the use of NSM FRP strips to enhance torsional behavior of RC beams. In these experiments, eight RC beams were tested to evaluate the strength enhancement provided by NSM strips to all four faces of beams (full wrapping) and to only three faces of the other four beams (U-wrapping). Test results showed that the fully wrapped beams achieved better performance than that of partially strengthened and unstrengthened beams. Other tests on FRP-strengthened RC beams subjected to torsional effects were also carried out and summarized in Table 4.

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Table 4 List of selected tests conducted on RC beams subjected to torsion

Researchers	Year	FRP material type	Strengthening system	Program details and Main findings
Ghobarah et al. [111]	2002	CFRP/GFRP	Sheets	Eight beams were strengthened by FRP wraps using different configurations and then tested under simply supported conditions. These tests have shown that complete wrapping and/or application of 45° spiral wrap to the torsion zone of in a RC beam is more effective for torsional strengthening than using individual (discontinuous) sheets. This is due to the fact that inclined fibers can maintain tensile stresses up to failure, while the vertical fibers are subjected to forces that are not along the direction of the fibers. In general, fully wrapped beams sustained a torsional moment of about 72% higher than that carried by control beam.
Hii and Al-Mahaidi [112]	2007	CFRP	Sheets	Six solid and box-section reinforced concrete beams with externally bonded carbon fiber-reinforced polymer (CFRP) were tested. These tests have documented an increase to both cracking and ultimate torsional strengths of strengthened beams in the rage of 40-78% as compared to the control RC beam. Results of these tests were used to update Australian and American design expressions.
Chalioris [113]	2008	CFRP	Sheets/Strips	Fourteen rectangular and T-shaped simply supported beams were tested under pure torsion. Test results agreed with those noted by Ghobarah et al. [111] in which the use of continuous FRP sheets wrapped around the cross-section of beams along their entire length caused a significant increase in ultimate torsional capacity. Further, torsional failure of fully wrapped beams occurred through tensile rupture of CFRP sheets. The torsional capacity of CFRP strengthened RC beams increased by 1.5–2.8 times the capacity of the control RC beam.
Deifalla et al. [114]	2010	CFRP	Sheets	Six RC beams (two control beams and four CFRP-strengthened beams) were tested as continuous beams under combined shear and torsion. Outcomes of these tests showed that shear and torsion capacities as well as torsional stiffness were increased by 71% as compared to the unstrengthened RC beam. Further, Using the use of a hybrid anchoring system made of steel angle and an anchor bolt delayed the premature debonding failure of strengthened beams.
Rafeeq [115]	2016	CFRP	Sheets	Two strengthened beams were used to observe additional capacity through the bonding of CFRP wraps/sheets. These tests showed an increase of 63-180% of torsional load carrying capacity of the beams. For practical applications, the use of fully wrapped and anchored sheets was recommended in order to provide a continuous shear flow resistance mechanism in the bonded sheets.

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Al-Bayati et al. [110]	2017	CFRP	NSM	Six RC members were tested to evaluate torsional strength enhancement provided by different NSM FRP configurations and epoxy/adhesive types. Observations from carried tests showed that the ultimate torsional capacity of strengthened beams improved by almost 21.6-30.7% when using the epoxy based bonding agent while, the increase in torsional capacity was limited to 12.7-15.7% when using the cement-based adhesive. These tests have also showed that although torsional improvement of U-wrapped RC beams strengthening was lower than that achieved by fully wrapped beams, the use of U-shaped strengthening configuration may be more practical for some cases.

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3.4 Axial applications

One of the early uses of FRP materials was to strengthen bridge piers and columns post-earthquake events [1-3]. In such application, FRP sheets are commonly used, although some recent studies have proposed the use of NSM reinforcement as well [116]. Lateral confinement of concrete columns by means of spirally wrapping FRP composites, as shown in Fig. 6, onto the concrete surface can increase compressive strength and inhibit longitudinal steel reinforcement buckling. In one study, Fardis and Khalili [117] pioneered and introduced the application of FRP materials to concrete columns. In another study carried out in early 1990s, Yamamoto [118] conducted experimental tests to investigate the feasibility of using FRP materials as strengthening and confinement systems for concrete columns. Yamamoto investigated the effect of FRP addition to uniaxial concrete strength and shear-flexural behavior of RC columns. Outcome of these tests revealed that ultimate strength of strengthened columns has significantly increased by about three times over original capacity of columns.

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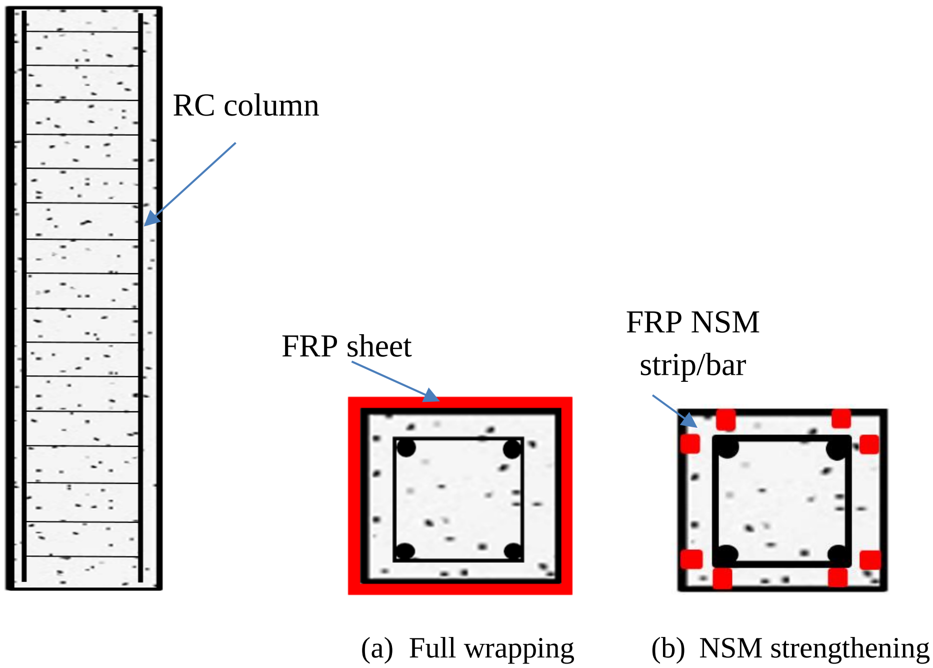

Fig. 6 Illustration of use of FRP for axial strengthening in RC columns

In more recent studies, Siddiqui et al. [119] tested a total of twelve small-scale circular RC columns. The columns were strengthened using varying layers of FRP sheets (1, 2 and 4 sheets). Results from these tests indicate that CFRP wraps provided adequate confinement to concrete as well as sufficient lateral support to longitudinal fibers, thus increasing strength and ductility of RC columns. Siddiqui et al. reported that the effect of longitudinal FRP fibers can be more pronounced in slender columns. A similar study was also conducted by Rahai and Akbarpour [120] who tested a total of eight large-scale rectangular RC columns strengthened with CFRP sheets. In this investigation, several parameters like number of CFRP sheets, fiber orientations (i.e. ±45°, 0°, 90°) and eccentricities in the direction of both weak and main axis were studied. Rahai and Akbarpour reported that increasing longitudinal layers rather than transverse layers led to a greater load carrying and displacement capacity because of the overall behavior of RC wall-like columns.

Walls, as conventional vertical elements, may undergo severe damage arising from various loading events. Further, redesigning buildings to improve space efficiency, fulfil updated codal requirements, and accommodate new services is often essential during their service lives to comply with functional demands. As a result of such changes, introduction of new openings in elements such as walls, inevitably reduces their structural performance and hence often require strengthening. For instance, Antoniades et al. [121] tested six RC cantilever walls with aspect ratio of 1.5 to failure and subsequently repaired and strengthened using anchored FRP sheets. Test results have shown that strength of walls can be increased by using conventional FRP systems. Li and Lim [122] presented results of an experimental study on the seismic performance of axially loaded FRP-strengthened RC walls with limited transverse reinforcement. Results showed that significant drift capacities were achieved from strengthened walls although similar performance to the original walls, before repair, in terms of the flexural behavior, shear strength, and ductility was achieved.

Further, Mosallam and Nasr [123] conducted tests that aimed at evaluating structural performance of RC shear walls, with various built-in opening geometries, and strengthened with CFRP laminates. Experimental results indicated that installed FRP lamination systems for RC walls was successful in improving both strength and ductility of strengthened walls. In the reported tests, the average strength gain and ductility enhancement of the retrofitted walls, as compared to the unstrengthened walls, ranged from 20% to 28%. A similar study was also carried out by Popescu et al. [124]. These authors tested nine RC walls, designed to represent typical wall panels in residential buildings that ranged between 25 and 50% reductions in cross-sectional area, to failure. Popescu et al. found that FRP-confinement and mechanical anchorages to RC walls increased their axial capacity with small and large openings by up to 63%. Further related studies axial strengthening of RC columns and walls can be found and summarized in Table 5. Besides experimental studies of columns with externally bonded sheets, several researchers used FE method to model the behavior and predict the strength of axially loaded concrete columns confined with FRP sheets [125-131]. Yu et al. [125] and Yu et al. [126] presented a critical review and assessment of the ability of the existing Drucker–Prager concrete plasticity model and the plastic damage model to predict the behavior of confined concrete using both experimental observations and FE results. They pointed the limitations of both models in simulating concrete under non-uniform confinement with FRP. However, they showed that FE predictions are in close agreement with the existing experimental results. Hany et al. [127] presented a modified concrete damaged plasticity model with new set of strain hardening/softening constitutive relationships for both actively confined concrete and FRP-confined concrete and developed a concrete dilation model. The developed model is applicable to a wide range of concrete strength and different column shapes. The FE results obtained using the developed modified model showed good agreement with test data for FRP confined concrete columns reported in the literature.

Furthermore, Lo et al. [128] used FE model for nonlinear analysis of axially loaded FRP-confined rectangular concrete columns and the results were verified against specimens with rectangular sections from existing experimental studies. There is close agreement between the FE results and the experimental ones. Teng et al. [129] carried out a 3D finite element analysis for circular FRP-confined RC columns and transverse steel reinforcement. The proposed FE approach

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demonstrated accurate results for both FRP-confined and steel-confined RC columns as compared with existing experimental results. Youssf et al. [130] developed a FE and analyzed a set of over 100 FRP-confined specimens with different unconfined concrete strengths and different confinement moduli. The proposed model predicted the experimentally obtained stress-strain curves, confined ultimate strength and confined ultimate axial strain very successfully. However, the prediction was less accurate for the confined ultimate hoop strain.

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Table 5 List of selected studies associated with FRP-strengthening of RC columns and walls

Researchers	Year	FRP material type	Strengthening system	Program details and Main findings
Ballinger et al. [132]	1993	CFRP	Sheets	Highlighted the potential uses for FRP materials in strengthening bridge piers and chimneys in Japan, bridge beams in Europe as well as various uses of FRP composites to strengthen structures in the U.S.
Lombard et al. [133]	2000	CFRP	Sheets	Performed tests on rehabilitated RC structural walls using CFRP sheets. In these tests, the comparative behaviour of the control wall with that of strengthened walls revealed that bonding CFRP sheets increased the ultimate strength of the strengthened walls by 25-39%. CFRP sheets also increased the stiffness of these walls at failure by 53-190%. Based on these tests, a simple analytical model was derived and then calibrated using similar test data.
Ye et al. [134]	2003	CFRP	Sheets	Eight RC columns, including two FRP-strengthened specimens, were tested under constant axial load and lateral cyclic load. In these tests, the strengthened columns achieved a higher ductility response in the range of 3-5.7 of that of the unstrengthened columns. It should be noted that the fully wrapped column achieved the best seismic performance as well as highest ductility index.
Zaki [135]	2013	FRP	Any	Presented an optimization procedure for retrofitting RC columns using FRP materials. This optimization was carried out using Gauss–Seidel technique to investigate number of parameters including thickness of FRP sheets and the wrapped length of columns subjected to axial loading together with end moments. This study also developed design charts to determine optimal length and thickness of FRP strengthening systems at different load levels.
Mohammed and Malek [136]	2013	CFRP	Sheets	Tested sixteen small-scale CFRP-strengthened RC wall panels with varying openings sizes of 5, 10, 20 and 30% were provided in the walls as percentage of total wall area. Test results indicated that load carrying capacity of CFRP-strengthened walls with openings improved due to beneficial addition of 45° CFRP wraps which reduced the principal stresses acting on the upper corners of the openings.
Li et al. [137]	2013	CFRP/GFRP	Sheets	Two structural RC walls with multiple irregularly and regularly distributed openings strengthened with CFRP sheets were tested. Tests showed that CFRP strengthening could improve lateral resistance of strengthened walls by 7-36%. Li et al. also noted that although application of strut-and-tie model can be effective in designing strengthening schemes for walls with openings, this model can be further improved through FRP anchors.

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3.5 Combined loading (seismic) applications

While the most studies focused on the static and monotonic behavior of FRP-strengthened structures, the seismic response of such strengthening systems has also been a focal point of investigation. The cyclic behavior of FRP-strengthened structures was thoroughly investigated due to the fact that FRP was mainly developed as an efficient retrofitting tool, especially in the case of seismically damaged buildings and bridges. One such study was carried out by Barnes and Mays [138] who reported cyclic (fatigue) tests on two RC beams and three RC beams strengthened with CFRP plates. Results from these tests indicated that beams failed in a primary flexural mode with no distinguishable differences in behavior between the strengthened and non-strengthened beams. Papakonstantinou et al. [139] also examined the effects of GFRP sheets on the fatigue performance of seventeen RC beams. They noted that beams failed primarily due to yielding of steel reinforcement and debonding of GFRP sheets was a secondary failure mechanism.

In more recent studies several researchers have investigated beams under cyclic loading [140-143]. Tanarslan et al. [140] tested seven identical deficient RC cantilever T-beams under cyclic loading. The beams tested in this experimental program were strengthened with side bonded, U-wrap, L-shaped, U jacketed, and double L-shaped jacketed FRP systems. Tanarslan et al. showed that the use of 2 and 3 layers of the CFRP strips yielded an increase in the failure load by 5.31% and 14.38%, respectively. In a parallel study, Sakar et al. [141] also experimentally and numerically investigated the behavior of RC beams externally strengthened in shear with NSM GFRP rods. A total of five RC cantilever beams were experimentally tested under cyclic loading. These researchers observed that the use of GFRP-NSM strengthening system has significantly enhanced the ductility of the tested beam specimens. The displacements at failure (ductility) of the strengthened specimens were more than that of the unstrengthened beam that ranged between 112% and 172%.

Totuanji et al. [144] studied cyclic performance of large scale concrete beams strengthened with bonded with three layers of CFRP sheets. Results have showed that both the load capacity and fatigue life of RC beams were significantly improved with addition of CFRP sheets. In particular, the fatigue strength of the strengthened specimens was increased by 55% as compared with that of unstrengthened beams. Hosny et al. [145] also tested twelve FRP-strengthened T-beams with hybrid combination of CFRP and GFRP sheets. The strengthened beams in this study achieved moderately higher failure loads, of about 10-30%, over that of the unstrengthened beam specimen. Other similar studies on the FRP composites in seismic applications are provided and summarized in Table 6.

The cyclic response of FRP strengthened beams can also be studied through application of FE simulation. For example, a number of researchers were able to successfully develop two and three-dimensional models that can accurately simulate FRP-strengthened beams subjected to cyclic loading. Some of these models were of a simple nature [146] while others were able to account for complex features such as bond-slip behavior between FRP and concrete beams and prestressing effects [147-150]. One of these studies was conducted by Vecchio and Bucci [146] who developed a simple nonlinear FE algorithm to analyze repaired or rehabilitated concrete structures. Another study was also carried out by Zhang and Shi [147] in which they were able to simulate debonding at rebar/concrete interface of FRP strengthened RC beams under cyclic

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loading. More recent studies used advanced FE software packages such as ANSYS, ABAQUS etc. (see Table 6). It should be noted that Kim and Hefferman [151] presented a detailed review study on fatigue behavior of externally strengthened concrete beams with FRPs.

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Table 6 List of selected studies carried out on seismic strengthening of RC beams using FRP composites

Researchers	Year	FRP material type	Strengthening system	Program details and Main findings
Ghobarah and Said [152]	2001	GFRP	Sheets	Externally strengthened beam-column joints in moment resisting frames were tested. The GFRP-strengthened beam-column achieved a moderate increase in failure load. Tests also indicated that the strengthened RC joint underwent a lower rate of deterioration in strength with higher ductility response (increased by 60%).
Sharbatdar [153]	2003	CFRP	Reinforcing rebars	Tested six cantilever FRP-reinforced beams subjected to lateral cyclic loading. Obtained results indicated that FRP-reinforced beams subjected to cyclic loading were not able to develop a plastic response due to the elastic nature of CFRP materials (except from that arising from concrete cracking). The tested beams underwent 3% drift which can be considered sufficient for earthquake applications.
Hosny et al. [145]	2006	CFRP/GFRP	Sheets	Behaviour of twelve RC beams strengthened with hybrid FRP laminates was examined through tests. The ultimate carrying capacity of the beams increased by 10.3-69.7% as compared to the control beam. Results from tests indicated that using U-wraps to anchor longitudinal GFRP sheets prevented debonding and rupture of FRP sheets. Hosny et al. proposed bonding sides of the beam with CFRP sheets (at 20 mm measured from the soffit) and using U-wraps made of GFRP sheets.
Karayannis, and Sirkelis [154]	2008	CFRP	Sheets	The experimental program comprises 12 external beam–column joint connection sub-assemblages tested under cyclic loading. The strengthened joints were shown to achieve up to 186% increase in failure load.
Sakar et al. [141, 155]	2014, 2009	CFRP	Sheets	Six T-beams were strengthened with side-bonded (uni- and bi-directional) CFRP sheets and then tested in a cantilever-like set-up. The ultimate strength of CFRP-strengthened beams increased in the range between 1.94 and 2.16

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	times that of reference beam. The predicted shear capacity of tested beams also was in close agreement to that predicted from ACI 440 design expressions with a maximum variation of 9%.

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4.0 Performance of Concrete Structures under Various Environmental Conditions

While FRP materials behave adequately at most conditions, the matter of the fact is that composites can be significantly affected by the surrounding environment. This section reviews selected experimental and numerical studies in which FRP strengthening system was subjected to harsh conditions such as elevated temperatures (fire), saline conditions, as well as cycles of freeze and thaw. It should be noted that due to the increased use of FRP in strengthening of RC structures, most reported studies investigated the performance of FRP materials and FRP-strengthened concrete structures under extreme effects. Unfortunately, the performance of FRP-strengthened MTMG structures under harsh environmental conditions did not gain the same level of attention and has rarely been reported. It is due to the scarce of tests and experimental programs as well as brevity and length consideration of this paper that such topics are not fully addressed herein. For more information regarding such effects, the reader is encouraged to review these relevant studies [156-159].

4.1 Elevated temperatures

In early years, FRP strengthening systems were mostly used in bridges where fire safety is not usually a primary design consideration. However, in the case of buildings, widespread application of FRP systems is being hindered due to concerns regarding FRP performance at elevated temperature [160-162]. These mentioned concerns arise from the fact that not only that strength, stiffness properties of FRPs are severely deteriorated at moderately temperatures [163-166] but leads to rapid and significant degradation in bond between FRP and concrete surfaces, which is critical to maintain the effectiveness of the strengthening systems. This is due to the low

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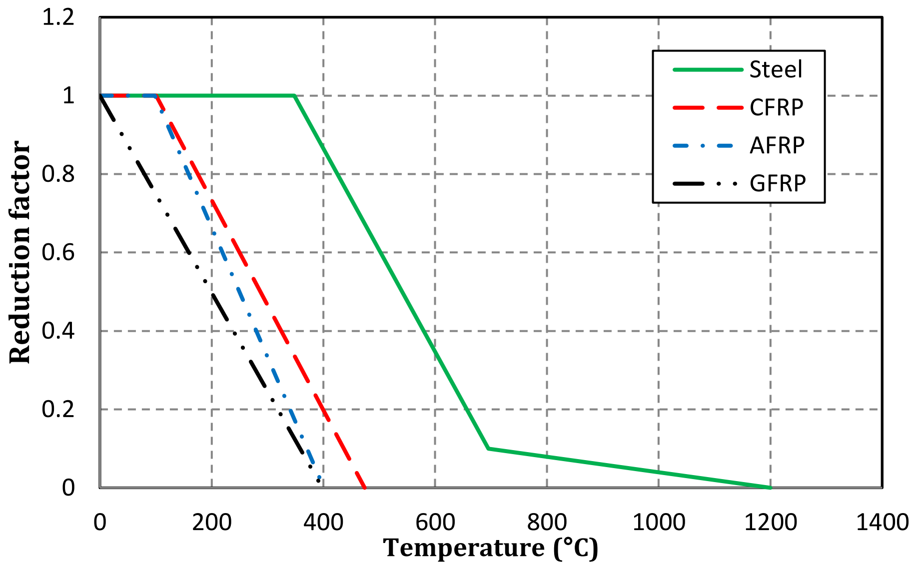
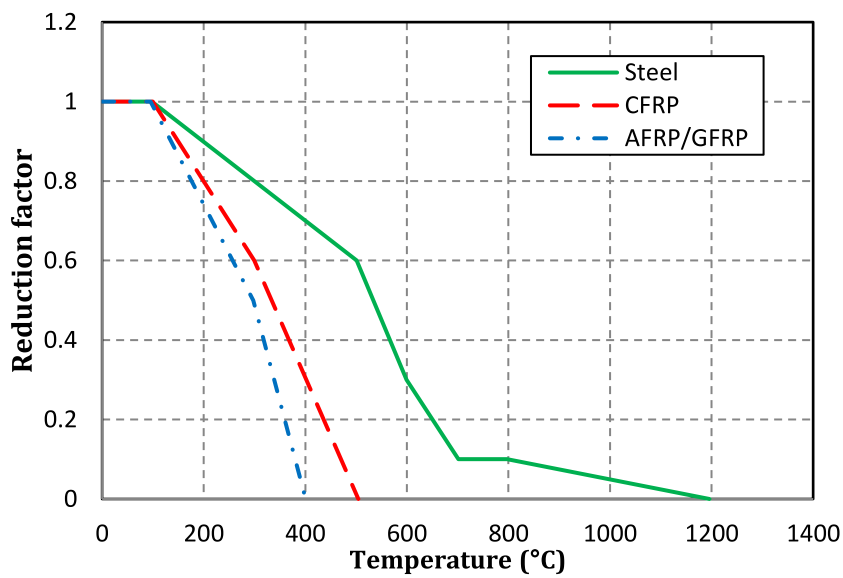
glass transition of the epoxy adhesive that ranges between 65–120°C [163-165]. Further, organic matrix of FRPs tend to decompose when exposed to temperatures in the range between 300 to 500°C, releasing heat, smoke, and toxic gases. Bisby [160] and Saafi [166] demonstrated effect of elevated temperature on various mechanical properties on FRP and structural steel (see Fig. 7).



(a) Temperature reduction factor for tensile strength



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(b) Temperature reduction factor for modulus of elasticity

Fig. 7 Effect of elevated temperature on mechanical properties of FRPs and structural steel [166]

Although research on the performance of FRP-strengthened concrete members exposed to fire is quite lacking and needs further investigation, still few studies have been conducted on the performance of FRP-strengthened concrete beams subjected to fire exposure. Among them, Deuring [167] who was one of the first researchers to conduct fire tests on externally strengthened concrete beams subjected to standard fire exposure. In his experiments, Deuring observed that the unprotected FRP-strengthened beams can achieve a fire endurance of 81 minutes. This is in contrast to an identical beam with the protected FRP systems which achieved a fire endurance of 146 minutes. Blontrock et al. [168] also tested, in a similar fire test program, a series of 10 CFRP-strengthened reinforced concrete beams protected with calcium silicate boards. In this experimental study, several insulation parameters were investigated, including board thickness, length, location, and bonding method. It was observed that the best fire endurance can be achieved through U-shaped fire protection systems applied to both the base and sides of the beams. These tests also showed that FRP starts to debond at temperatures close to the transient glass temperature of 55-60°C. The loss of interaction between FRP and concrete was reported to occur with the first 40 minutes of exposure to the standard fire.

A more recent study was carried out by Williams et al. [169] who experimentally investigated the performance of two CFRP-strengthened reinforced concrete T-beams insulated with vermiculite gypsum (VG) insulation under standard fire conditions. The results of this investigation indicated that a properly insulated system can maintain the FRP and reinforcing steel

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materials below a certain critical temperature value that sustains their structural integrity. It was also concluded that one layer of VG insulation can protect the beam during fire exposure and achieve fire endurance of more than 4 hours. These researchers also pointed out that while FRP stiffness appears to suffer negligible losses up to approximately 400°C (above which it decreases rapidly), CFRP and GFRP lose about 50% of their original strength at 250 and 325°C, respectively.

Similar tests on rectangular beams and slabs were also carried out and summarized in Table 7. Outcomes of these tests seem to converge on the fact that RC members whether strengthened with FRP plates or NSM, can be significantly improved by addition of fire protection systems, specifically to anchorage zones. It should be noted that few experimental studies investigated fire response of FRP-reinforced concrete beams, these studies have shown that thickness of concrete cover tend to control fire resistance of such beams [170-172].

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Table 7 List of selected fire tests carried out on FRP-strengthened RC beams

Researchers	Year	FRP material type	Strengthening/Reinforcing system	Program details and Main findings
Bisby [160]	2003	CFRP	Sheets	Presented results of two full-scale fire tests on CFRP-wrapped and insulated RC columns. Results from fire tests showed that FRP-wrapped RC columns that are adequately insulated can achieve a 5 hour fire rating under standard fire conditions.
Ahmed and Kodur [170]	2011	CFRP	Plates	Four RC beams were tested after being strengthened with CFRP plates. Despite high rise in CFRP temperature, presence of cooler anchorages outside the fire exposed zone helped in contributing to the load-carrying capacity of FRP-strengthened RC beams. Ahmed and Kodur recommended that FRP-strengthened RC beams to have a minimum of 25-50 mm thick protection system, to survive 3 hour exposure to standard fire.
Palermi et al. [171]	2012	CFRP	NSM	Twelve reinforced concrete beams were strengthened in flexure with NSM FRP bars and insulated with different insulation schemes and then tested. Although these beams were subjected to high service load, all the beams were able to sustain the applied load for 2 hours of fire standard exposure.
Yu and Kodur and [172]	2014	CFRP	NSM	Four RC T-beams, strengthened with NSM FRP reinforcement, were tested by subjecting them to standard fire exposure and service load conditions. Fire test results showed that NSM CFRP strengthened RC beams can achieve 3 hours of fire resistance under standard fire exposure (even without any fire insulation).

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4.2 Saline environment

Infrastructures located near areas with high humidity and moisture content (marine environment) often experience accelerated rate of steel and/or steel reinforcement corrosion. Steel corrosion leads to several defects including reduction in the cross-sectional area of the steel section (i.e. flange), timber swelling, concrete and masonry cracking [1, 2]. As a result of such defects, these structures often require retrofitting. Unfortunately, humidity and saline exposure can also cause significant reduction in bond stress of the FRP-bonded surface interface which jeopardize integrity of the strengthening system [1, 3]. Chlorides may be especially severe in marine environments or cold regions where salt deicing is used. This has been documented in number of review [173] and research studies [174].

Recent tests have shown that resin properties may strongly influence the durability of FRP reinforcement: particularly GFRP material. Unlike glass fibers, carbon fibers cannot absorb liquids and thus are resistant to acid, alkali and organic solvents [175]. Also, they do not show considerable deterioration in saline environments. On the other hand, GFRP laminates are vulnerable to moisture because of their high absorption capabilities and fact that most epoxies absorb between 1% and 7% moisture by weight. Absorption is mostly caused by diffusion due to a concentration gradient and also to relaxation swelling of the composite. Tests on the effects of saline water immersion on plates of GFRP, revealed that it can lower the mechanical properties by 17% after 3000 hours of immersion. Other studies carried out by Rostasy [175] revealed that GFRP behavior degrades when it is in permanent contact with dissolved salty solutions within a short time of exposure (1000 hour). Further test data on AFRP showed that strength can be reduced by

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55% to 60% in alkaline solution. These tests also showed that CFRP is durable in usual environments compared to GFRP and AFRP materials.

Chajes et al. [176] showed a 36% decrease in ultimate strength for GFRP retrofitted specimens that were subjected to 100 wet/dry cycles, while a 19% reduction was shown for CFRP bonded specimens. Toutanji and Gomez [177] observed a strength reduction up to 33% on specimens made of different epoxies and subjected to 300 wet/dry cycles in saltwater. Failure was reported as a debonding mode that generally took place near the FRP-concrete interface. On another separate study, Silva and Biscaia carried out an extensive experimental program on effects of artificial environmental aging including saline water immersion [178]. They found out that exposing concrete specimen to saltwater immersion caused improvement of concrete properties due to additional curing of concrete however, these specimens achieved higher slip under applied loading. It was also found that the first 1000 hours of exposure to saline environment did not significantly affect FRP material, whereas at an exposure of 10,000 hours (about 13 months), the interface at the FRP/concrete surfaces was strongly affected.

Almusallam and Al-Salloum [179] also investigated the effect of completely or partially immersion of GFRP bars-strengthened specimen tap-water and sea-water. The results show that there is significant loss in tensile strength of GFRP bars when subjected to sustained stress for the considered exposure conditions. Porter et al. [180-181] carried out two test programs to investigate long-term strength of GFRP composites through accelerated aging procedure. In these tests, GFRP specimens were exposed to an alkaline solution at high temperature (up to 60°C) for up to 2000 hours which is equivalent to a 50 year natural exposure. The outcome of these tests quantified loss

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in strength in the range of 34-71% of the initial strength. Sultan et al. [182] reported similar 50-60% strength loss for 10–15 year exposure in hand laid-up GFRP sheets, and bars, respectively. Table 8 lists other tests and studies carried out in this area.

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Table 8 List of selected experimental studies carried out on FRP-strengthened RC structures subjected to saline environment and freeze/thaw cycles

Researchers	Year	FRP material type	Strengthening system	Program details and Main findings
Karbhari and Zhao [183]	1997	FRP	Plates	The effect of short-term environmental exposure on the response of in situ formed externally composite strengthened concrete specimens was investigated. Outcome of tests showed that CFRP material displayed a lower degree of overall deterioration as compared to GFRPs in exposures of sea/fresh water as well as cycles of freeze and thaw.
Ellyin and Rohrbacher [184]	2000	GFRP	Any	A comparative study is carried out to evaluate the properties of dry and water immersed GFRP-specimens, and to investigate damage caused by the aqueous environment and temperature. Test results showed that GFRP materials tend to absorb water and swell, however this absorption can be neglected at temperature below 35°C. It was also noted that strength and ductility of GFRP materials tend to slightly decrease as a result of immersion in water of temperature of 90°C.
Subramaniam et al. [185]	2008	FRP	Sheets	Influence of freeze–thaw action on FRP–concrete interface fracture properties was investigated. Subramaniam et al. showed a consistent decrease in the load carrying capacity of the specimens subjected to freeze–thaw cycles when compared. The average length of the stress transfer zone for control was also shown to decrease. For instance, effective bonded length of specimens subjected to 100, 200 and 300 freeze–thaw cycles were 92, 82, 78 and 68 mm, respectively.
Robert and Fam [186]	2011	GFRP	Tubes	GFRP tubes filled with concrete and subjected to salt solution for 365 days at temperatures up to 23-50°C were investigated. These tubes lost a maximum of 21% of their hoop tensile strength. This reduction in tensile strength was found to be a function of exposure temperature. For example, increasing the temperature of the solution from 23 to 50°C resulted in further loss in tensile strength from 11 to 21% at the end of exposure period.
Shi et al. [187]	2012	BFRP	Sheets	Basalt fiber–reinforced polymer (BFRP) sheet and concrete substrate were tested under the coupled effects of freeze-thaw cycling and sustained loading. Shi et al. reported that bond-slip parameters i.e. ultimate load, global slip, interfacial fracture energy and maximum shear stress decreased, whereas the effective length increased with increasing numbers of freeze and thaw cycles. It was also noted that failure mode of tested specimen also changed from debonding at the concrete surface to debonding in adhesive layer with increasing freeze-thaw cycles.
Silva et al. [188]	2014	CFRP/GFRP	Laminates	Tests conducted FRP-strengthened beams subjected to dry/wet and cycles of salt fog. Outcome of such tests showed that glass transition temperature of the epoxy used in the GFRP-reinforced beams increased in the first 3,000 h of aging, due to a postcure phenomenon, and then decreased due to plasticization effect. The tests on the CFRP-strengthened RC beams also showed that environmental conditioning at 10,000 h caused a decrease in carrying load capacity for salt fog exposure.

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Mohammadi et al. [189]	2017	FRP	Sheets	Twenty four specimens were maintained in the experimental alkaline conditions for 3,000 h. In general, alkaline condition led to a significant reduction in the bond strength. Results from carried tests indicated that specimens exposed to an alkaline solution at 23°C experienced decreases in their load carrying capacity by 4.7-23.3%. When the temperature increased from 23°C, to 60°C, the change in bond strength took a very slower reduction.

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4.3 Cycles of freeze/thaw

A large number of reinforced concrete structures in need of repair are located in regions that regularly experience fluctuation in weather conditions. Thus, durability of FRP strengthening systems to weather conditions has been an interest to many researchers [176, 185 , 179-180] (also see Table 8). One of the primary concerns for the application of FRP to civil infrastructure repair is the long-term behavior of the bond between the FRP composite and the existing structure under harsh environmental conditions such as freeze–thaw cycles. Freeze–thaw cycles been known to cause progressive degradation of the FRP composite as well as interfacial bond at FRP–concrete. This could result in a steady decrease in load carrying capacity and hence the service performance of strengthened and retrofitted structural elements, need to be evaluated.

The adverse effects of freeze–thaw cycles have been recently studied by number of researchers [187, 189-193]. For example, Chajes et al. [176] noted that CFRP material has a much higher environmental durability than either GFRP or AFRP. Further, test results showed that GFRP and AFRP strengthened beams lost about 50% of their strength gain after freeze-thaw cycling, whereas CFRP strengthened beams lost only 9% of the ultimate strength. Another study was conducted by Subramaniam et al. [185] who demonstrated results from an experimental investigation on the influence of freeze–thaw cycles on the CFRP–concrete interface fracture properties using direct shear tests. These authors monitored stress transfer between FRP and concrete through Digital Image Correlation (DIC) method and reported a 17% decrease in ultimate load due to freeze–thaw cycles.

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Soliman et al. [194] tested twenty CFRP and GFRP bars in pull-out setup to failure after conditioning though 200 cycles of freeze/thawing. Soliman et al. noted that due to temperature change arising from different cycles, hair cracks developed in the bonding materials which triggered a strength loss between 8-14% as compared to the reference specimens. Karbhari et al. [195], in a review paper, indicated that freezing temperature exposure results in matrix hardening, microcracking of matrix, and overall bond degradation. Such effect, in presence of salt, can result in accelerated degradation due to expansion of salt deposits in addition moisture swelling and drying which eventually lead to debonding of FRPs.

Other studies have reported no changes in FRP-strengthened members after exposure to freeze and thaw cycles. One such study was carried out by Green et al. [191] and Mukhopadhyaya et al. [192]. Mukhopadhyaya et al. noted that ultimate strength of the bond between FRP and concrete was not affected, however failure mode changed from concrete shear failure to adhesive failure after being exposure to freeze and thaw cycles. Surprisingly, few studies have reported that FRP-strengthened specimens have experienced improved performance post-exposure to similar conditions. For example, Green et al. [193] reported that single lap shear specimens exhibited ultimate strength increases up to 54% after the freeze-thaw exposure and failure mode progressively changed from concrete shear failure to adhesive failure. Ultimate strength of small-scale beam specimens increased, and mid-span deflection increased after exposure as well.

5.0 Challenges, and Future Research Needs

The above literature review indicates that FRPs have great potential for continual integration into civil engineering applications. These materials have superior properties, and thus can be employed in a variety of construction applications. In general, FRP materials can revolutionize conventional design of modern structures, specifically to those utilizing concrete or masonry. Unfortunately, like any other construction material, FRP composites have few limitations that hinder designers of utilizing these systems to their full potential [196-202]. This section aims at highlighting few of these limitations, associated challenges, and required future research needs.

The simplest way to enhance any construction material, such as FRP, is to improve its inherent material properties. Once FRP's material properties are improved, then many of the limitations related to utilizing materials can be overcome. In fact, a closer look at recent development of structural steel reveals that corrosion of steel girders was one of the main issues related to steel construction. This significantly limited use of such material in outdoor applications (i.e. bridges, outdoor construction etc.). However, advancement in material science has led to development of corrosion-resistant "weathering" steel which is commonly used in bridge construction nowadays. Similar steps can be carried out to improve material properties of FRP composites, in terms of their performance at extreme conditions such as freeze/thaw cycles, saline environment and elevated temperature, etc. This can significantly promote the use of FRP into more civil-related applications. Such advancement is not only needed to enhance FRP material properties but can also be extended to develop improved adhesives and installation techniques (such as mechanical anchoring systems, prestressing systems, etc.). It is worth noting that employing such advancements would be vain if cost of improved FRP (or adhesives) is significantly decreased. Hence, developers should also consider optimum cost implications on market share of FRPs.

In lieu of improving inherent material properties of composites, a systematic and broader study of accelerated environmental effects on moisture diffusion on FRP–concrete bond, chloride and salinity effects is required. Better understanding of such effects and how they can affect structural response of FRP-strengthened/reinforced members can lead to mitigating poor performance under actual loading conditions. Durability and sustainability of FRP systems continues to be a pressing issue that warrants further investigation. Such investigation can be carried out through experiments which would set basis towards developing numerical and analytical models. Since experiments can consume large monetary and time resources and have limitations due to availability of testing equipment and qualified operators, developing such models could be used as valid tools to carry out design oriented parametric studies. Outcome of these studies could provide raw data to derive and calibrate design expressions which maybe then used in codes and standards for design and analysis purposes.

The collection of studies presented in this paper reveals interesting findings, specifically towards the fact that variation in reported test results tend to have large margins (in the range of 50-75% difference in some cases) and it may not even be consistent. This can be attributed to significant variation in tested specimens, material types, loading configurations, experimental procedures, and test arrangements, etc. which make interpretation of test results complex and not feasible. This leads to a call for standardization of testing procedures. Thu some test standards are published [203-205], more standardization efforts are needed to cover additional weather conditions, duration of tests, types of test specimens, qualification of testing individuals, etc.

Furthermore, it would be certainly intriguing to analyze and test some of the early FRP-strengthened/reinforced constructions to investigate long-term performance of such structures. This might shed more light into actual behavior of such structures at real application and under actual service and weather conditions. Such investigation can also lead to developing real-like environments to be reproduced (replicated) in laboratories. This can significantly enhance practicality of experimental tests and better link it to on-site applications. Fortunately, recent technological advancements have led to developing various types of sensing devices which can be installed in new FRP-strengthened/reinforced constructions. With the aid of such devices, real-time or near real-time monitoring of structural/physical/chemical facilities can be accessible to researchers and designers as to better understand performance of such structures during their service life. Modern FRP systems, such as Fibre Reinforced Cementitious Matrix (FRCM), FRP anchors etc., are becoming accessible and widely accepted [205-207]. Systematic and collaborative investigations covering aspects of manufacturing, performance, and durability of these systems are warranted.

Summary & Conclusions

The above literature review clearly indicates that FRPs have great potential for continual integration into strengthening of RC structures. These materials have superior properties, and thus can be employed in a variety of construction applications. In fact, FRP materials have revolutionize conventional design of modern reinforced concrete structures. Unfortunately, like any other construction material, FRP composites have limitations that hinder designers from utilizing these systems to their full potential. As discussed earlier, a companion study highlights some of these limitations and associated challenges specifically relating to performance of FRP materials and FRP strengthening systems when subjected to fatigue, seismic and impact loading as well as when exposed to extreme conditions such as elevated temperature, saline environment and cycles of freezing and thawing.

This paper presents a literature review on some of the early (classic) and recent experimental, numerical and analytical studies associated with the integration of FRP strengthening systems in concrete structures. The outcomes of this review can be summarized in the following points:

- FRP materials can be an integral part of modern design of structures due to superior properties of FRP composites and their potential in developing structural systems that exceed those constructed by traditional materials.
- The major contribution of FRP composites is its potential to extend service life of existing structures.
- FRP systems are very versatile and easy to install which come in handy in flexural, shear, torsional and axial retrofitting applications.
- There is limited research on the use of FRP strengthening systems for torsional applications in RC beams and also for axial applications in RC walls. Further research with regard to such application is warranted specifically on the use of ductile FRP materials (PET, PEN) and hybrid systems.

- The available database on the behavior of FRP-strengthened beams, slabs and walls with openings need to be further enriched with results from new tests and numerical investigations.
- Performance of FRP-strengthened/reinforced structures is limited by the performance of FRP materials and systems under surrounding loading and environmental conditions.
- The implementation of new technologies (such as sensing devices) can provide better insights to long-term behavior of FRP-strengthened concrete structures.

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