Review Article
Volume 10:4, 2020
DOI: 10.37421/jcce.2020.10.354

Journal of Civil & Environmental Engineering

ISSN: 2165-784X

Open Access

Structural Strengthening/Repair of Reinforced Concrete (RC) Beams by Different Fiber-Reinforced Cementitious Materials - A State-of-the-Art Review

Sifatullah Bahij[1,2], Safiullah Omary[1]*, Francoise Feugeas[1] and Amanullah Faqiri[2]

[1]Icube, UMR CNRS 7357, INSA de Strasbourg, 24 Boulevard de la Victoire, 67084, Strasbourg, France
[2]Department of Civil and Industrial Construction, Kabul Polytechnic University, Kabul, Afghanistan

Abstract

In the last few decades, premature deterioration of reinforced concrete (RC) structures has become a serious problem because of severe environmental actions, overloading, design faults, and materials deficiencies. Therefore, repair and strengthening of RC elements in existing structures are very important to extend their service life. There are numerous methods for retrofitting and strengthening of RC structural components such as; steel plate bonding, external pre-stressing, section enlargement, fiber-reinforced polymer (FRP) wrapping, and so on. Although these modifications can successfully improve the load-bearing capacity of the beams, but they are still prone to corrosion damage resulting in failure of the strengthened elements. Therefore, many researchers used cementitious materials due to their low-cost, corrosion resistance, and resulted in the improvement of the tensile and fatigue behaviors. Different types of cementitious materials such as; fiber-reinforced concrete (FRC), high performance concrete (HPC), high strength concrete (HSC), ultra-high performance concrete (UHPC), steel fiber-reinforced high strength lightweight self-compacting concrete (SHLSCC), fabrics reinforced cementitious material (FRCM) and so on have been used to strengthen structural elements. This paper summarizes previously published research papers concerning the structural behaviors of RC beams strengthened by different cementitious materials. Shear behaviors, flexural characteristics, torsional properties, deflection, cracking propagation, and twisting angle of the strengthened beams are explained in the present paper. Finally, proper methods are proposed for strengthening RC beams under various loading conditions.

Keywords: Reinforced concrete beams • Strengthening techniques • Fiber-reinforced cementitious materials • Mechanical strengths • Crack pattern • Twisting angle

Introduction

Reinforced concrete (RC) is a combination of concrete and steel reinforcement. Unreinforced concrete has adequate compressive strength but low tensile strength, which results in concrete deterioration under lower traction or flexural applied loads. Therefore, steel reinforcements are needed inside plain concrete for improving the tensile performances [1-3]. It is highly required to update and modernize structures for economic rising and prosperity. For this purpose, improvement is needed in entire infrastructures, particularly RC structures as they will be exposed to severe degradation due to the influence of freeze-thaw, aggressive environments, de-icing salts, and overloading. Hence, it is a decisive issue for civil engineers to protect, retrofit, and maintain these deteriorating structural elements with the execution of new, low-cost repairing techniques to extend the lifetime of deteriorated and new structures [4-8].

Several studies have been conducted to identify various techniques and materials to restore damaged structures and strengthen the new structural elements. Fiber-reinforced polymers (FRPs) are the most commonly exploited materials for strengthening and repairing purposes. Researches were performed to study the behaviors of strengthened structural members with FRP and observed many useful outputs. However, the applications of FRPs contains some deficiencies, which prevent the execution of FRPs under cyclic loading in compression. These performances depend on the parent concrete strength, the bond behaviors between FRPs and concrete, and their durability [9]. Thus, new cementitious materials were generated and applied to repair and strengthen damaged or new RC structural elements, known as fiber reinforced concrete (FRC), high-performance concrete (HPC), high strength concrete (HSC), ultra-high performance fiber reinforced concrete (UHPFRC), steel fiber reinforced high strength lightweight self-compacting concrete (SHLSCC), fabrics reinforced cementitious material (FRCM) and etc. Many researchers underlined the two important features of these concretes (durability and strength) that show promising results [10-12].

These cementitious materials are the newest generation of concrete and are used in many civil engineering applications. Almost two decades ago ultra-high performance concrete (UHPC) has been invented and characterized by steel fibers, cement, micro silica, sand, superplasticizer, and very low water-cement ratio (w/c) [13]. These cementitious materials have high tensile and compressive strengths, high ductility, low permeability, and good durability because of their condensed microstructures. UHPC permits designers to select thinner sections and longer spans for structural elements [14,15]. The incorporation of steel fibers into UHPC improves their mechanical behaviors, reduces their brittleness, and changes the crack propagation performances [16]. Therefore, UHPC was considered for the rehabilitation and strengthening of the structural members. The main purpose was to utilize UHPC to strengthen those parts that are exposed to severe environmental conditions. Furthermore, research investigation has found that UHPC has a perfect bond with ordinary concrete to be used for repair and strengthen techniques, and rough surface preparation contributes to a higher bond [17].

The outcomes of an experiment on RC slabs strengthened with UHPC illustrate that UHPC reduced and postponed cracks growth, demonstrated excellent energy absorption, and increased the ultimate load capacity [18]. An experimental investigation was carried out to examine the structural behaviors

***Address for Correspondence:** Safiullah Omary, Icube, UMR CNRS 7357, INSA de Strasbourg, 24 Boulevard de la Victoire, 67084, Strasbourg, France, Tel: +33751522716; E-mail: safiullah.omary@insa-strasbourg.fr*

Received 22 July, 2019; **Accepted** 27 July, 2020; **Published** 03 August, 2020

of strengthened beams and found that UHPFRC considerably improves the structural performance of RC elements [8]. Researchers studied the efficiency of UHPFRC in strengthening existing RC structures and underlined the excellent performances of RC beams strengthened with UHPFRC 3-sides jacketing [19]. In addition, flexural strengthening of RC beams or slabs with UHPC were studied and found that UHPC could be used to improve such properties of RC elements [20]. Flexural properties of RC beams strengthened by engineered cementitious composites (ECC) were investigated and the results demonstrated that beams strengthened at the tension zone or sides displayed better strength and ductility characteristics compared to the control ones [21]. An experimental and numerical study was conducted to investigate the shear behaviors of RC beams strengthened by steel fiber reinforced concrete (SFRC) precast panels. The findings present that the shear behavior of the beams strengthened by SFRC panels was remarkably enhanced. In addition, nonlinear finite element analysis also found strong agreement with the experiments [22]. Besides the experimental studies, several researchers have conducted the finite element method (FEM) to simulate the structural elements in recent FEM software. In this context, the researchers found a good agreement for UHPC beams studied by experimental and FEM methods [23]. In order to better understand the structural behaviors of the strengthened/repaired RC beams, a wide-ranging literature review was performed to evaluate the current state of the art for flexural, shear, and torsional-strengthening of RC beams using various fiber-reinforced cementitious materials. Moreover, the main aims of this review article are to emphasize on the effective strengthening schemes for flexural, shear, and torsional strengthening, and to investigate the deflection and failure mechanism of RC beams using these strengthening materials.

Highlights

- Fiber-reinforced cementitious materials have the perfect bond with the host concrete.
- Shear, flexural, and torsional load capacities of strengthened RC beams have improved.
- Load capacity of sandblasting method was lower than the epoxy adhesive technique.
- UHPFRC is the most recommended materials for strengthening and repair of RC beams.

Literature Review

Fiber-reinforced cementitious materials

Scientists have tried to find a proper solution for the brittleness behaviors of materials from the very beginning of civil engineering applications. Previously, organic fibers have been incorporated into their mixtures to modify the brittleness of clay bricks but recently steel fibers are satisfactorily used to improve the behaviors of cementitious materials [24]. It is reported that more than 30 companies produce steel fibers and more than 100 types of steel fibers are produced worldwide. Mostly straight fibers were manufactured during their first productions, but more than 90% of steel fibers have been recently produced as a shaped fiber to increase their anchorage in concrete mixtures. Moreover, the fibers were produced over the last 40 years in twisted, crimped, flattened, spaded, coned, hooked, surface-textured, and melt-cast shapes of various diameter and lengths [25]. Ultra-high performance concrete (UHPC) is a recent type of fiber-reinforced concrete and has been characterized by fine steel fibers (2-10)%, no coarse aggregate, a high volume of fine aggregate, a high range of water reducing agent (superplasticizer), micro silica and low water-cement (w/c) ratio. UHPC possesses high compressive, flexural and tensile strengths, high toughness, high elastic modulus, low permeability, adequate freezing and thawing resistance, low carbonation depth, self-compacting behavior, high durability, dense microstructure and etc [26,27]. Experimental work was performed to examine the mechanical properties of UHPC and found that compressive strength was 150MPa, modulus elasticity was 47GPa and flexural strength improved to 35MPa [28]. Fiber-reinforced concrete is used in many civil engineering applications such as industrial floors, roads, airports, shell structures, railways, tunnels, reservoirs, bridges and etc. For example, several bridges in Canada, Korea, Japan; roof structures in France and Netherland; the cooling tower of a power station in France and etc. Coming to the point, many researchers found through their research investigations that fiber-reinforced cementitious materials are known as the most effective materials for strengthening and repairing activities, therefore, they reported these materials [29,30].

Bond between normal concrete and fiber-reinforced cementitious materials

Bonding properties between the host concrete (ordinary concrete) and the strengthening materials is one of the most important issues in rehabilitation processes. Several researchers have conducted experimental work and found a perfect bond between these two materials, and recommended fiber reinforced cementitious materials to strengthen and repair the structural elements. Experimental work was performed to study the bonding properties between normal concrete and UHPFRC. In this context, various tests were carried out such as; slant-shear test with the inclined bond interface at 55°, 60°, and 70°, pull off, and splitting tensile tests for two different bonds methods, epoxy-bonded (EP), and sandblasted (SB). The outputs present that normal concrete specimen with rough surfaces made by sandblasting present higher slant shear strength compared to epoxy-bonded ones. Furthermore, the findings of splitting tensile strength reported a perfect bond between normal concrete and UHPFRC [31]. Similarly, split tensile strength and slant-shear tests were conducted to measure the bond strength between the host concrete and ultra-high performance fiber concrete (UHPFC). The results indicated that UHPFC provides perfect bonding at the early repairing age, and works strongly together with the surface of the normal concrete [32]. Moreover, experimental work was carried out and found excellent bonding between the host concrete and UHPC. The outputs of the tensile splitting test highlight that the failure commonly happened in normal concrete samples. This means that UHPC bonded very powerfully and efficiently with the normal concrete, where the wire brush and scabbing techniques behave almost monolithic [17].

Strengthen of RC beams by fiber-reinforced cementitious materials

Commonly, the RC beams are strengthened/repaired to improve their flexural, shear, torsional, and other structural behaviors. In this context, several research investigations have been conducted to examine the structural behaviors of the RC elements strengthened by various cementitious materials. Although most of the studies were performed only as research but some findings have been put into practice and have shown excellent performances as well. In fact, these properties are directly related to the types of fiber-reinforced cementitious materials, retrofitting configurations, and adhesive materials. This section aims to underline and summarize some of the recently performed research investigations regarding the flexural, shear, and torsional strengthening of RC beams using various cementitious materials.

Flexural behaviors

Flexural strength, also recognized as rupture modulus and is the highest stress of material just before its yielding in a flexure test. The flexural strength of concrete beams is generally measured using rectangular cross-section or T-shaped samples and with the help of 3-point or 4-point loading setups [33,34].

In this regard, experimental and numerical work was performed to evaluate the flexural behavior of RC beams strengthened by UHPFRC. Overall 6 beams were prepared and tested: 2 of them as control specimens, 2 beams were strengthened by UHPFRC layers, and 2 others were strengthened by combined UHPFRC layers and steel bars. UHPFRC was produced from the mixed proportion of sand, silica fume, ground granulated blast furnace, CEM I 52.5 R, polycarboxylate superplasticizer, 3.0% of steel fibers by volume (13 mm long and 0.16 mm diameter), and w/c ratio of 0.28. The layers of UHPFRC were attached to the RC beams by shotcrete or proper formwork. The outputs indicated that the attachment of UHPFRC layers resulted in increased stiffness and first and ultimate flexural load capacities. While the UHPFRC layer plus steel bars resulted in a significant enhancement of these load capacities over the control ones. Moving to the crack pattern, the control beams started with the first cracks at lower loads, and then crucial cracks for failure of the beams were found in the middle of the span, and finally, beams failed at both compressive and tensile zones. The beams strengthened with the UHPFRC layers started with the first cracks on the UHPFRC layer and propagated toward RC beams, while some local debonding was seen at the interface and eventually the beams failed at the compressive zone. For beams strengthened by combined UHPFRC and steel bars, the first crack began at flexural zones and followed by a single crack propagated through the UHPFRC layer and resulted in beams' failure. In addition, the bonding at the interface was found to be strong enough and no debonding has happened even during the final failure. The authors reported almost zero slip value at supports and the highest value of slipping was observed near the loading points. Finally, the experimentally tested beams were modeled numerically in ATENA software and the results show a good agreement with the experimental outputs [35].

In the same context, the experimental and numerical study was carried out to investigate the flexural characteristics of RC beams strengthened with the UHPFRC layer by two techniques:

a) Bonding *in-situ* UHPFRC layers using sandblasting, and

b) Bonding with the prefabricated UHPFRC layers using epoxy adhesive. In total, 8 beams were prepared and considered 3 different configurations:

  - Bottom side,
  - Two longitudinal faces, and
  - Three sides strengthening and the jacketing thickness in each configuration was 30 mm.

The outputs underlined that flexural load capacity improved remarkably for the strengthened beams compared to the control ones. As a comparison, the beams strengthened in 3-sides experienced more improvement than beams strengthened just in the bottom portion. In addition, it was observed that beams strengthened using epoxy present higher load capacity than strengthened with sandblasting technique. Moving to the crack pattern, almost all beams strengthened with the help of sandblasting/epoxy failed in flexure that was started in the mid-span and propagated toward the supports. However, beams strengthened at the bottom showed a combination of flexural and splitting flexural cracks. While beams strengthened in 3-sides had fewer cracks due to the combination of side and bottom jackets, and the flexural cracks during failure were more concentrated to the mid-span. The beams' load-deflection behavior was almost similar, the load was increased linearly with a slight decrease in stiffness during cracking up to yielding of the steel reinforcement. However, the beams strengthened with UHPFRC experienced higher stiffness compared to the control specimens because with the application of UHPFRC jackets the natural axis comes down. Additionally, the authors simulated the tested beams with the help of a nonlinear finite element method using ABAQUS software. The concrete damage plasticity model (CDPM) was considered to model concrete, while the behaviors of the materials were directly inputted into ABAQUS from the results of previously tested samples. The findings show that the outputs of FEM were best fitted with the experiments [31].

The research work (experiments, analytical, and FEM) was carried out to analyze the flexural behaviors of RC beams repaired by UHPFRC. Totally, 7 beams were prepared: a control specimen, 3 beams were repaired with different thicknesses of UHPFRC layers on the upper side, and 3 others were strengthened on the bottom side with various thicknesses of UHPFRC jackets. The UHPFRC layers consist of steel fibers that contain 13 mm length and 0.16 mm diameter. The results indicated that beams strengthened with UHPFRC jackets show higher flexural load capacity compared to the reference one. This is attributed to the high strength and strain hardening properties of UHPFRC. In comparison, the enhancement was more for beams containing thicker jacketing because a thicker layer contributes to smaller deformations for a given load and the creation of localized micro-cracks at higher loads. In addition, beams strengthened on the lower side showed better behavior than strengthened on the upper side. Moving to the crack pattern, all beams failed in flexure; the control beams failed in flexure with concrete crushing, while strengthened beams also failed in flexure but with UHPFRC crushing or rebar fracture. Moreover, it was observed that strain at the top of the control and strengthened beams reached the crushing value and resulting in concrete crushing at the fracture load. Except for the beams strengthened at the lower side had the same strain distribution behavior as the reference one, but strain at the top exceeded the crushing value, and bottom steel bars fractured because the strain was reached to the ultimate. The authors also conducted the analytical flexural model and finite element model by using nonlinear FEM software of MSC/Marc. They considered a perfect bond between reinforcements, concrete, and UHPFRC layers. The supports were modeled on plates as a roller with constraining to a single line of nodes at plates. Concrete was considered as a homogenous and initially isotropic material. It was found that analytical and FEM results best match the experiments. However, some differences were reported such as; the analytical model and FEM found that beams were stiffer than experiments. This is attributed to the fact that the experiment contains dry shrinkage, heat evolution during hydration, handling of RC beams that will cause micro-cracks [36].

Moreover, experimental work was carried out to study the flexural behavior of RC beams strengthened with UHPFRC laminates by different bonding techniques and rebar addition. The authors conducted the experimental work in three steps: 1) material characterizations to obtain a proper mix design among four percentages of steel fibers (1.0%, 2.0%, 3.0%, and 4.0%), whereas, 3.0% of steel fibers were selected in terms of both strength and workability, 2) testing of UHPFRC laminates to obtain the bare properties of full-scaled laminates, and 3) testing of RC beams strengthened with UHPFRC laminates in order to examine their flexural properties. Two bonding techniques were applied for strengthening, epoxy resin, and mechanical anchorage. In addition, steel bars were also added into some specimens. The findings highlighted that overall flexural load capacity increased, while beams were strengthened with UHPFRC laminates independent of the bonding method. However, this improvement was more significant for beams strengthened with the help of epoxy resin compared to the mechanical anchorage due to its high tensile strength. In addition, considerable improvement was highlighted, while steel bars were also added into RC beams. On the other hand, all the beams failed in flexural with fracture of laminates, but little difference was observed in cracking initiation, number of cracks, and their locations. In the epoxy resin method, the failure mode was changed from flexural to brittle concrete cover separation without the failure of UHPFRC laminates. In this case, the deflection has reduced because laminates act as rigid plates, and deflection decreased more, while steel bars were added into the beams. Besides, the beams strengthened with the help of mechanical anchorage also failed in flexure, but they were containing concrete crushing and failure of laminates [37].

Similarly, research work was conducted to analyze RC beams strengthened and repaired with high-performance fiber reinforced concrete (HPFRC). The authors considered 4 beams including a control one, beam without steel bars but strengthened by HPFRC, beam containing both steel bars and strengthened jackets, and RC beams repaired by HPFRC. The strengthening materials were obtained from the mix proportion of cement, silica fume, aggregates, superplasticizer, and steel fibers (12 mm length and 0.18 mm diameter). The results indicate a perfect bond and no-slip between host concrete and strengthening materials (HPFRC). The un-strengthened RC beam initiated with flexural bending cracks at 50kN load between two loading points, then cracks were developed to lose the bonding between reinforcement and concrete, and finally, the beam failed in flexure with debonding. On the other hand, the beam strengthened by HPFRC but without steel bars collapsed brittle at 258kN load with a single crack developed close to the mid-span. The RC beam strengthened by HPFRC has presented similar behaviors as the second one due to the presence of jacketing. Since the beam is reinforced a slight reduction in stiffness was observed due to cracks initiation, and finally, the beam collapsed with a single crack near support that contains longitudinal reinforcement rapture as well. The authors also pointed-out that HPFRC jacketing leads to a remarkable improvement in load capacity of the beams and this improvement was 2.15 times for the strengthened beam with steel bars. Additionally, the above-tested beams were numerically analyzed with the help of FEM software DIANA. A 3D model containing iso-parametric 20 nodes brick elements was selected for both concrete and steel reinforcement, and perfect bond was considered between steel and concrete, and between concrete and HPFRC. Generally, it was documented that FEM results were in a perfect agreement with the experimental outputs. However, some differences were recorded between these two findings. For example, variation in the stiffness of the RC beam without jacketing, which could be explained by the presence of splitting cracks in experiments but not existing in FEM due to the perfect bond. In addition, the HPFRC jacketing technique was also considered to repair the pre-damaged beams. The repaired beams had the same properties as the strengthening ones. Where the first cracking loads were similar as was observed for the strengthened beams, but the initial stiffness of the repaired beams was slightly lower than the strengthened ones. The improvement in load capacities of the repaired beams was lower than the strengthened ones [38].

In the same token, experimental work was performed on the RC beams strengthened by steel fiber-reinforced high strength lightweight self-compacting concrete (SHLSCC) to compare its results with the stress model. The mix design of SHLSCC contains: rolled and crushed coarse aggregate, fine aggregate, CEM-I, superplasticizer, fly ash, and steel fibers with the dimensions of 12 mm length and 0.2 mm diameter. Totally 8 beams were cast: one beam as a reference, one was made with half of the normal concrete and half of SHLSCC, and 6 others were strengthened by various thicknesses (40, 50, and 60) mm of the SHLSCC layers. For each strengthening thickness; one beam was considered as a pre-cracked and one as un-cracked. It was highlighted through the results that enough bond and no-slip was detected between the old concrete and SHLSCC, which prove the usage of SHLSCC to strengthen RC members. In addition, the authors noted a significant improvement in both stiffness and flexural load capacity of strengthened beams compared to the reference one and this improvement was more for beams containing a thicker layer of SHLSCC. It was well documented that beams strengthened with U-shaped jackets showed the highest load capacities among all beams. Pre-cracked strengthened beams showed slightly lower flexural load capacities than the un-cracked beams. It was also found that the developed models are more effective to predict the flexural behavior of the beams strengthened with SHLSCC jackets [39].

A research was conducted to investigate the flexural behaviors of the RC beams strengthened by highly ductile fiber-reinforced concrete (HDC) and reactive powder concrete (RPC). A total of 12 beams were prepared and divided into 4 groups; 3 beams as a reference, 3 were strengthened by 30 mm thick HDC at the tension zone, 3 were strengthened with 30 mm thick HDC at the compression zone, and 3 others were strengthened with 30 mm thick RPC at the compression zone. The results highlighted that the ultimate flexural load capacity remarkably increased for the beams strengthened by the HDC layer at the tension zone. The flexural load capacities of the beams strengthened by HDC or RPC in the compression zone have also increased but such improvement was less compared to the beams containing strengthening layers in the tension zone. In addition, this enhancement was more for RPC-based strengthened beams than HDC-based ones. Generally, stiffness decreased for the beams strengthened by HDC or RPC and resulted in greater mid-span deflection compared to the control beams. However, beams strengthened by HDC in the tension zone had more stiffness and resulted in mid-span deflection reduction than retrofitted in the compression zone. Moreover, the control beams had elastic behavior before cracking, whereas the first cracks initiated in the bottom portion of beams, as the load was increased, more cracks were found and then widened between supports. Here, longitudinal reinforcements were yielded, the cracks extended to the compression zone followed by concrete crushing. For the beams strengthened by HDC, the initiation of first cracks were delayed but was found at the bottom, then widened and propagated toward the HDC layer. As the load was increased, firstly, the steel bars inside the HDC layer were yielded, then followed by original bars yielding, and eventually, concrete in the compressive zone was crushed. The delay in cracks occurrence is because of the high ultimate tensile strain of HDC. Overall, beams strengthened with HDC or RPC had fewer horizontal cracks, but beams with the HDC layer experienced debonding between the HDC layer and normal concrete at the end of loading, while the RPC layer had a good bond with the host concrete. The reason behind a good bonding between the RPC layer and host concrete is RPC's high compressive strength [40].

A research study was conducted to investigate the flexural behaviors of the RC beams strengthened by engineered cementitious cement (ECC) + BFRP grids. Overall, 4 beams were prepared, one beam as a control specimen, and the other 3 were strengthened by 30 mm ECC and 1 mm, 3 mm, and 5 mm thick BFRP grids at the tension zone. The results show that ultimate load capacity remarkably improved for the strengthened beams and this improvement was more for a thicker layer of BFRP sheets. In addition, stiffness of the strengthened beams significantly increased compared to the control sample. Moving to the crack pattern, a flexural crack with concrete crushing was reported for the control beam. While beam strengthened with 1 mm and 3 mm thick BFRP grids, the rupture of BFRP grids at the mid-span was detected and followed by concrete crushing. Finally, the beam strengthened with a 5 mm thick BFRP grid was failed in flexure with debonding and BFRP grids fracture. Furthermore, there was no slip between the strengthening materials and the host concrete which shows the perfect bonding of the interface [41].

Similarly, a research investigation was conducted to study the flexural behaviors of RC beams repaired by various types of concrete. In total 15 beams were prepared and strengthened with four different types of concrete; UHPC, UHPFRC, normal strength concrete (NSC), and cement-based repaired material (CRM). From this, 3 beams were considered as control specimens, and 12 others were previously cracked and then strengthened with the help of the above four types of concrete. The authors found the flexural load capacity increased, while beams were repaired independent to the type of materials. However, this improvement was more for beams strengthened by UHPFRC, then CRM, followed by UHPC, and finally normal strength concrete. In addition, the repaired beams present less mid-span deflection and enhanced stiffness than the control ones. This is attributed to the high modulus of elasticity of repairing materials. As a comparison, the beam repaired by UHPFRC had the least deflection, then beam repaired by CRM, followed by a beam with UHPC, and finally, the beam that contains NSC as a repair material. Moving to the crack pattern, the crack pattern of all the repaired beams is flexure outside the repaired area. However, the beams repaired by UHPFRC and CRM experienced less widen and shorter cracks compared to the control beam and beams strengthened by UHPC and NSC [42].

Furthermore, a research study was performed to explore flexural behaviors of the RC beams retrofitted by HPFRC, designated CARDIFRC. In total, 32 beams were prepared; 4 beams were considered as references and the remaining 28 were strengthened with different configurations using epoxy as adhesive materials. The variable parameters were, retrofitting configurations, mix proportion of HPFRC, and the thickness of retrofitting layer. The results illustrated that retrofitting of RC beams by HFFRC not only enhanced the flexural load capacity, but also increased remarkably the serviceability of the beams in terms of a reduction in the number, width and length of the cracks. As comparison, the beams retrofitted by U-shape strips had the highest load capacity and the least mid-span deflection in both mix proportion compared to the other configurations. Secondly, the beams strengthened at the tension zone and at sides had higher load capacity and stiffness than beams strengthened only at the tension zone. In addition, the flexural load capacity and stiffness increased with the increase of strips thickness in both mix proportion. It was also observed that HPFRC containing long steel fibers were more effective in term of load capacity than with short fibers. Moving to the crack pattern, almost all control beams failed in flexure, but beams strengthened by HPFRC, the cracking mode changed from brittle shear to flexure or flexure-shear. This illustrated the HPFRC can be used effectively to the effectiveness of the strengthening configurations and materials. Finally, an analytical model was developed according to the stress-deformation diagrams of the Model Code CEB-FIP to predict the flexural behaviors of the RC beams that were experimentally tested. It was documented that the outputs for all control and retrofitted beams were well fitted with the experimental outcomes [43].

Additionally, experimental work was carried out to strengthen RC beams with the help of steel fiber-reinforced high strength lightweight self-compacting concrete (SHLSCC). Four various configurations were considered: no layer, 1-layer at the tension zone, 3-sides jacketing, and a half beam from normal concrete and a half from SHLCC. Overall, the peak load and stiffness of the strengthened beams considerably increased at any strengthened configuration. However, this improvement was more for 3-sides jacketed beams and specimens containing a thicker layer of SHLSCC compared to the control beams [44].

In the same context, research works were carried out to study the flexural behaviors of RC beams strengthened by fiber-reinforced cementitious materials with various configurations. The outcomes illustrate that these materials are recommended to improve the structural behaviors of the deteriorated or new structural members. In addition, the improvement level directly depends on the type of cementitious materials, strengthening method, adhesive materials and etc [45-47]. Table 1 shows the relative percentage of the ultimate flexural load capacity and mid-span deflection, and cracking pattern for the strengthened RC beams.

Shear behaviors

Shear behavior is the most important property of the RC beams because shear failure is more dangerous than flexure one for concrete structures because of its sudden happening. Shear failure is mostly initiating from shear zones near supports and occurring without giving pre-alarming alerts. Shear behavior of the RC beams strengthened with different fiber-reinforced cementitious materials was experimentally and numerically studied by many researchers.

An experimentally and numerically study was performed to investigate shear behaviors of the RC beams strengthened by ultra-high performance concrete (UHPC) jackets. In total, 9 beams were considered with two variable parameters: a) shear span to effective depth ratio, a/d (1.0, 1.5, and 2.0), and b) strengthening configuration (2-sides and 3-sides jacketing). In each a/d ratio one beam was considered as a reference, and two others were strengthened with two different configurations of 30 mm thick UHPC jackets. Prior to beams testing, split tensile and slant tests were conducted and their results proved a good bond between normal concrete and UHPC. The experimental results demonstrated that beams strengthened by 3-sides jacketing and having a lower a/d ratio had the highest load capacities compared to the others. Moreover, shear load capacity of the beams containing a/d=2 significantly decreased compared to the beams having a/d=1 and a/d=1.5. In addition, load capacity of the beams in each group was remarkably enhanced, while strengthened configuration has been changed from 2-sides to 3-sides jacketing, but this effect was disregarded for the beams with a/d=2. On the other hand, it was reported that the control beams failed in pure shear, and then the failure mode has been changed to shear-flexure for 2-sides or 3-sides strengthened beams. This proves the effectiveness of the strengthening materials to change brittle shear failures to shear-flexure ones. Besides, the 3-sides strengthened beams showed extremely ductile behavior with lesser cracks, therefore, 3-sides strengthening configuration is strongly recommended for strengthening and repair purposes. Finally, nonlinear FEM was conducted in ABAQUS software. From the FEM results, it was observed that beams' shear behaviors such as; load capacity, stiffness, deflection, load-deflection curve, and cracking pattern predicted by ABAQUS were in good agreement with the experimental results [48].

Similarly, experimental and numerical work was carried out on shear behaviors of the RC beams strengthened by pre-fabricated UHPFRC plates. The UHPFRC plates were prepared from concrete with a mix proportion of sand, silica fume, fly ash, CEM I 42.5 R, and end hooked steel fibers with the dimensions of 30 mm length and 0.8 mm diameter. In the present experimental work, 7 beams were prepared and the variable parameters were, stirrups spacing, longitudinal bars ratio, various configuration, and thickness of jackets. The findings present that shear load capacity enhanced for the strengthened beams and such improvement was more, while number of the stirrups or width of the beam has been increased compared to the control one. As a comparison, 2-sides strengthened beams showed considerably higher load capacity and mid-span deflection than beams strengthened at one side. However, shear behaviors have been improved more, while steel reinforcement was added to the 2-sides strengthened beam. Therefore, it was summarized that the beam retrofitted at both sides and with steel bars was strongly proposed and recommended for the purposes of strengthening and repair. On the other hand, beam strengthened at one side and without steel bars had a higher load capacity than control specimens, but debonding occurred between normal concrete and UHPFRC layer during failure, but this debonding was eliminated with the introduction of steel bars. Moving to the crack pattern, the un-strengthened beams failed in brittle shear, while for the strengthened beams, the failure modes have been changed from brittle shear to ductile flexure, which shows the effectiveness of the UHPFRC materials for the strengthening purposes. In addition, the authors numerically investigated the tested beams and considered nonlinear FEM software of ABAQUS. It was reported by the numerical study that a good agreement between experimental and FEM results was detected, and it was documented that FEM is able to obtain the best-fitted shear behaviors (load-deflection curve, peak load, cracking pattern) of the RC beams [49].

In the same manner, experimental work was conducted to examine the shear properties of RC beams strengthened with HPFRC jackets. Overall, including a reference specimen, 4 beams with different configurations and adhesive materials were prepared and tested. The outcomes underlined that the control beam showed an elastic behavior up to 50kN load, then started with the first cracks between the loading points. At the load of 200kN, shear diagonal cracks were initiated between supports and loading points, followed by shear cracks widening, and finally, the beam failed in shear. On the other hand, the strengthened beams showed similar behaviors, where the cracks initiated in the middle spans and then propagated deeper inside the beams. Since the load was increased, diagonal cracks were found and then mid-span cracks were widened up to beams failure. It was also observed that the strengthened beams did not collapse suddenly but showed some ductile behavior after failure and had improved stiffness compared to the control one. Generally, shear load capacity and mid-span deflection have improved for the strengthened beams compared to control ones independent of the strengthening method. To compare, shear load capacity and deflection decreased, while thixotropic material was applied instead of self-leveling material in the beams' lateral faces. Such load capacity decreased more, while the jacketing thickness has decreased from 50 mm to 30 mm [50].

Additionally, research was carried out to measure the shear strength of RC beams strengthened by ultra-high strength fiber-reinforced concrete panels (UFC). In the present study, it was proposed to retard cracks development with the introduction of UFC panels and to study the effect of UFC panels and beam size on shear strength. Overall, 5 beams were prepared; 2 beams were considered as control specimens, 3 others were strengthened by UFC panels. For the strengthened beams, 2 were considered with the half and quarter size of the real beam. For the quarter-size RC beam, 7 mm thick UFC panels were applied, while half-size beams were strengthened with 14 mm and 28 mm thick UFC panels. The results illustrated that both shear load capacity and mid-span deflection have been increased for the beams strengthened by UFC panels. To explain further, such improvements were significant for half size beams compared to the quarter size ones, and for the beams strengthened with the thicker layer of UFC. The crack pattern of quarter-size beams has changed from control specimens to the strengthened beams. It means that quarter size of control specimens failed in shear compression and such cracks were detected in the shear spans. Moreover, it was observed that transversal and longitudinal cracks were found in the bottom and edge of the strengthened beams and finally, the beams suffered a partial peeling failure in UFC plates. Lastly, the authors conducted an analytical model according to JSCE, 2002 recommendation, and found that the analytical results were in good agreement with the experiments [51].

A research was performed to analyze shear characteristics of the RC beams strengthened by epoxy mortar panel with steel fibers (EMSF). In total, 6 beams were prepared; a control beam and 5 others were strengthened by various thicknesses of EMDF materials. The researcher used new composite materials, named epoxy mortar with steel fibers (EMSF), which present high strength and toughness properties. The dimensions of EMSF were 700 mm length, 400 mm height, and 7.5 mm and 12.5 mm thickness. In addition, the authors considered two types of steel fibers (50 mm and 35 mm long) and different thicknesses of strengthened materials to evaluate the effect of steel fibers type, and thickness of the EMSF layer on shear behavior of the strengthened beams. The results underline that the control specimens started early with the flexural cracks at the bottom and center of the beams, then shear cracks were also started, and finally, the beams were failed in shear. While beams strengthened with the epoxy mortar and without steel fibers started with the shear cracks at 85% of the maximum load and finally, failed with brittle shear failure. For the beams strengthened with the epoxy mortar and short steel fibers, shear cracks initiated at 68% of the maximum load, such beams showed some ductile behavior and finally, interfacial fracture occurred with concrete debonding. The beams strengthened with the help of epoxy mortar that contains both types of steel fibers, showed more ductile behavior than the other beams. The highest shear load was underlined for the beams strengthened by short steel fibers and a thicker layer of epoxy mortar. While beams strengthened with epoxy mortar and long steel fibers exhibited best ductile behavior and were effective in preventing RC beams from brittle failure. To conclude shear capacity was significantly enhanced, while short steel fibers were added into concrete mixture compared to long fibers, and further increased for the beams strengthened with thicker epoxy mortar [52].

Experimental work has been conducted to analyze shear behaviors of the RC beams strengthened by high strength strain-hardening cementitious composites (HS-SHCC). In total, 8 beams were prepared and divided into two groups based on two different shear span to effective depth ratio S/D (1.5:1 and 2.5:1). Each group has two beams as references and two others were strengthened at both sides with 10 mm thick HS-SHCC layers. The HS-SHCC matrix was composed of cement, silica fume, sand, water, and polyethylene (PE) fibers (12 mm long and 24 µm diameter). The outcomes have been illustrated that the shear load capacity of the strengthened beams remarkably increased compared to the un-strengthened beams in both groups. Percentagewise, this improvement was more notable for the beams having a greater S/D ratio than specimens with a smaller S/D ratio. Moving to the cracking pattern, it was reported that the control beams have damaged with large diagonal shear cracks and less flexural cracks near the mid-span. However, strengthened beams initiated with closely spaced multiple cracks, as the load was approaching to the ultimate, minor detachment was found between RC beams and HS-SHCC. Finally, these beams were failed due to widen shear cracks and no spalling was observed because they were taken by HS-SHCC layers. It was also documented that bond performance between RC beams and the HS-SHCC layer was efficient [53].

A research study was performed to investigate the shear properties of the RC beams strengthened by the fabric-reinforced cementitious matrix (FRCM). Overall, 6 beams were produced in two groups based on the difference in concrete strength. In each group one beam was considered as a reference, another was strengthened with one ply of FRCM, and the remaining one was strengthened with 4 plies of FRCM. FRCM was the mixture of cement and the dosage of dry polymers lower than 5.0% in weight and reinforced with dry-fiber fabrics. The findings underlined that the shear strength for the beams strengthened by FRCM has increased and this improvement was more for the beams containing high strength concrete and 4 plies of FRCM. Moreover, the cracking pattern was based upon the number of plies. Slippage failure was recorded for a one-ply strengthened beam, while delamination from the substrate was detected for 4-plies strengthened beam. In addition, the analytical model was conducted according to the ACI code consideration. The results of the analytical model show that the prediction is underestimated because the tensile strength used in this model is not related to the fiber rupture but depended on the FRCM tensile coupon after the crack saturation zone [54].

Similarly, an experiment was conducted to study the shear behaviors of RC beams strengthened by polyparaphenylene benzobisoxazole fabrics-reinforced cementitious materials (PBO-FRCM). In total 10 beams were prepared and divided into two groups (no stirrups, 10 mm × 127 mm stirrups), each group contains one beam as a control specimen and 4 others were strengthened with different configurations. In addition, the U-wrapped sheets were applied for the strengthened beams with two configurations; separated strips (102 mm × 204 mm) and continuous strips (560 mm width). The variable parameters were stirrups existence or not, FRCM configurations, ply number, and ply width. The FRCM was a mix proportion of cement, silica fume, fly ash, less than 5.0% polymer, and glass fiber. The beams were strengthened in four steps;

1. Applying non-thixotropic mortar with polypropylene fibers to provide proper adhesion,
2. The first mortar layer was laid on approximately 3 mm,
3. The PBO mesh was placed, and
4. The second mortar layer was laid on over the PBO mesh and leveled to have a smooth finishing surface.

The outcomes indicated that both shear load capacity and mid-span deflection have increased for the strengthened beams in both categories (with stirrups and without stirrups). However, these enhancements were more for beams strengthened by PBO-FRCM and containing stirrups as well than the strengthened beams without stirrups, the beams strengthened by 4 plies of FRCM than one-ply, the beams strengthened with continuous strips than separate FRCM strips. Moving to the crack pattern, in the case of beams with stirrups, the load-deflection curve initially present linear behaviors for all tested beams, then the beams had different load-carrying capacity and failure mode. It means that the control beams failed in shear with the initiation of a single diagonal crack in shear spans. While the beams strengthened by separate strips were also failed with a diagonal shear crack but followed by slippage or rupture of FRCM. Furthermore, for the beams strengthened by continuous strips, the cracking pattern has been changed from shear to high ductile flexure. This includes the effective contribution of the continuous U-wrapped configuration because it provided higher strength and continuous confinement along the shear span. In the case of beams without stirrups, all beams failed with the initiation of a single diagonal tensile crack in shear spans. However, in the beams strengthened with four plies of the FRCM, there was no shear failure through the PBO-FRCM strengthening system. But a slippage of the PBO fibers out of the cementitious matrix was detected in the beam retrofitted by one ply [55].

Additionally, an experimental work was performed to explore the shear behaviors of the beams strengthened by steel fiber-reinforced concrete precast panels (SFRC). Overall, 9 beams were considered and the variable parameter were, volume fraction of steel fibers (0%, 1.0%, 1.5%), connection type (epoxy, epoxy + bolt), bolts diameter (10 mm and 12 mm), and numbers (4, 6, and 8). In each beam. 4 SFRC (300 mm length, 300 mm width, and 10 mm thickness) panels were used as an external reinforcement in shear spans. The results underlined that shear load capacity improved, while SFRC panels were attached to the beams. Furthermore, the increase in the percentage of steel fibers resulting in an increase in shear load capacity and stiffness due to the high modulus of elasticity of the steel fibers. On the other hand, the shear load capacity and mid-span deflection have increased with the increase of bolt numbers. While using epoxy + bolt instead of the only epoxy resulted in increased shear load capacity but a considerable reduction in mid-span deflection. Moreover, the increase of bolt diameter did not have much effect on shear load capacity and mid-span deflection. Moving to the crack pattern, almost all beams failed with diagonal shear cracks, where before the occurrence of flexural cracks, the initial load-deflection behavior linearly enhanced with the applied load, and then the stiffness of the beams slightly reduced with the initiation of flexural cracks. Thereafter, diagonal cracks were found in the shear spans and resulting in the abrupt stiffness reduction, finally, the beams failed in shear. However, for the beams strengthened by the only epoxy, shear failure occurred with the debonding of SFRC panels, while the deboning was prevented by epoxy + bolt connection. In addition, a high number of cracks were visible for the beams strengthened by concrete without steel fiber due to lower tensile strength of the mortar without fibers and number of the cracks has been decreased with the increase of volume fraction of steel fibers because the fibers make bridges in the strengthening materials. Furthermore, inserting bolts and increasing their numbers help the shear force to get transfer to the panels and also prevent the debonding of the panels, while the diameter of bolts has no significant effect on the crack pattern [22].

In addition, research work was performed to examine the shear strength of the beams strengthened by ultra-high performance fiber reinforced concrete (UHPFRC). The results highlight that shear load capacity has been considerably improved for the beams strengthened with UHPFRC compared to the control ones. Moreover, mid-span deflection has decreased for the strengthened beams because the strengthening layers increase the stiffness of the beams [56]. Additionally, research studies were performed to investigate shear performances of the RC beams strengthened by various types of cementitious materials. Overall, the outcomes indicate a remarkable improvement in shear load capacity and stiffness for the strengthened beams compared to the un-strengthened ones. The degree of the improvement is dependent on the type of cementitious material, strengthening configuration, jacketing thickness, and so on [57,58]. **Table 2** indicates shear behaviors of the RC beams strengthened with different types of cementitious materials and studied by various authors.

Torsional behaviors

Torsional strength is the ability of materials to sustain twisting loads, and it is the maximum torsional stress that materials sustain before the rapture.

In this regard, experimental work was carried out to study the torsional improvement of the RC beams strengthened by UHPC jackets. In total, 11 beams were prepared, one beam as a reference, 4 beams were fully wrapped (4-sides), 4 beams were strengthened with U-jacketing (3-sides), and 2 others were strengthened with 2-sides jackets, and each configuration had different thicknesses of UHPC layers. All the beams were tested under pure torsional loading setup, whereas one end of the beam was supported by roller support and the other end was supported by rigid support. The results present that beams containing 4-sides jacketing exhibited a significantly higher torsional capacity than beams with 3-sides and 2-sides UHPC jacketing. Moreover, in each configuration, torsional capacity was corresponding to the thickness of the UHPC layer, it means that thicker UHPC layer the higher torsional capacity. Moving to the crack pattern, the control beam has a wide range of cracks and a faster rate of crack progression compared to the strengthened beams. The crack propagation of the control beams was subjected to the pure torsion on the large faces of the cross-section because the faces undergo the largest shear stresses. Here, some diagonal cracks appeared, as the torsion was increased, the number of the cracks was also increased, and finally, the beam was failed, while one crack was significantly widened and load reached to its peak value. In comparison, the strengthened beams were initiated with the first cracks on the unwrapped face, then new cracks were started at the wrapped long faces, and finally, the ultimate failure occurred due to the formation of a single spiral crack around the beam. At the time of failure debonding was noticed between the RC beam interface and UHPC jackets. In addition, numerical modeling was conducted using ANSYS software to compare the experimental results with the FEM. Concrete was modeled as SOLID65 elements and steel reinforcements were modeled as 3D spar elements and Link8. The outcomes of the FEM show that there was strong agreement between the experimental and FEM results for both control and strengthened beams [9].

In the same context, experimental work was carried out to investigate the torsional behaviors of the RC beams strengthened by a fiber-reinforced cementitious matrix (PBO-FRCM). In total, 5 beams were prepared and tested. The beams were strengthened with different configurations: a control beam, the beam strengthened with a 3-sided configuration that the strips were 101.6 mm wide and with 101.6 mm clear spacing, a 4-sided configuration that FRCM was 101.6 mm wide and with 101.6 mm clear spacing, and fully wrapped without spacing. PBO-FRCM is the composition of a cementitious matrix and an unbalanced fiber net. The net is formed from rovings spaced at 10 mm and 20 mm on center, and 5 mm and 15 mm in the longitudinal and transversal directions, respectively. The strengthening process includes: the beam surface was sandblasted, cleaned from dust and water saturated, and then the FRCM layers were applied in two stages; first 3 mm and then 2 mm. In addition, linear variable differential transformer (LVDT) and rotational variable differential transformer (RVDT) and the strain gauges were applied to measure deflection, angle of twisting, and strains in the steel reinforcement, respectively. The results have indicated that FRCM jacketing provided an incredible improvement in the torsional capacity and angle of twisting. Generally, before cracking a linear behavior with high stiffness was detected for each strengthened beam. Then the angle of twisting increased without the increase of torque capacity due to the redistribution of forces from concrete to the steel bars. Finally, beams suffered non-linear behavior with a reduction of stiffness before they reached to the peak load. Regarding the cracking patterns, the control beam showed typical torsional behavior with spiral diagonal cracks around the beam cross-section. The beam strengthened at 3-sides had similar failure mode as control specimen, except that failure occurred near beams restrained end and was followed by concrete cover spalling. The 4-sides wrapped beams exhibited hairline cracks on the surface of composite, then fibers slippage happened, and finally, the beam failed due to fibers rapture followed by concrete crushing and loss of confinement at the mid-span. The strain value observed from shear reinforcement of the strengthened beams was almost similar as detected for the control beam at the torsional strength. In contrast, strains in the longitudinal reinforcement of the strengthened beams were much higher compared to the control ones. Therefore, it is sensible to accept that only the primary fibers were contributed to the improvement in torsional strength [59].

In the same context, research work was performed to evaluate the torsional behaviors of the RC beams strengthened by HPFRC composite mortar. Overall, four RC beams were prepared based on the strength of their cores and the cover over the concrete. The beams BN21 and BN40 were containing 21MPa and 40MPa concretes in the whole section, respectively. While BF1.5 and BF2.0 specimens were consisting of 21MPa concrete in the core and covered with the HPFRC layer that contains 1.5% or 2.0% of polyvinyl alcohol (PVA) fibers. The pure torsion test setup that contains the capacity of 300KN and loading speed of 1mm/s was used to test the beams. The outcomes demonstrated that the torsional load capacity has improved, while beams were prepared with the high strength concrete compared to the beams with low strength concrete. In addition, the torsional load capacity was significantly increased, while beams were strengthened by HPFRC mortar and this improvement was more for the higher percentage of the fibers. Moving to the cracking pattern, all the RC beams failed with the skew-bending-type of failure. However, the beams BN21 and BN40 showed more cracks than BF1.5 and BF2.0, because HPFRC mortar has high tensile ductility. These cracks were connected to the large cracks in beams BN21 and BN40 but were not connected to the large cracks for the beams BF1.5 and BF2.0, because fibers prevent cracks propagation. Furthermore, the crack angles of the beams BF1.5 and BF2.0 were smaller than BN21 and BN40 because of the longer effective torsional length of BF1.5 and BF2.0 compared to the beam BN21 and BN40. At the ultimate torque, the twisting angle was larger for the beams BN21 and BN40 compared to the beams BF1.5 and BF2.0. This is because of the presence of transverse reinforcement in the beams BN21 and BN40, which contributed to both the ultimate torque and twisting angle. Finally, the strain at the ultimate torque of the beams BF1.5 and BF2.0 were less compared to the beams BN21 and BN40, which means that the transverse reinforcement has less contribution in the torsional load capacity [60]. **Table 3** indicates the torsional behaviors of the RC beams strengthened with different types of cementitious materials and studied by various authors.

Results and Discussions

Table 1 summarizes that all authors agreed that fiber-reinforced cementitious materials used for strengthening and repairing purposes showed a perfect bond with the host concrete and has the ability to improve flexural behaviors of the RC beams. However, the improvement level is directly dependent on the type and thickness of the materials, number of the layers, bonding materials, applying technique, and type of configurations. Overall, it has been reported that the flexural load capacity of the strengthened beams with any type of fiber-reinforced cementitious materials has increased compared to the un-strengthened beams. This is because of the high strength and strain hardening properties of fiber-reinforced cementitious materials. However, such enhancement was more for the beams strengthened by UHPFRC, then retrofitted by HPFRC, and followed by other types of cementitious materials. In addition, the flexural load capacity improved with the increase of jacketing number and thickness because thicker layer results in a smaller deformation for a given load and formation of localized micro-cracks at higher loads. Moreover, the beams strengthened in the tension zone showed better behavior than strengthened in the compression zone. The flexural load capacity was higher for the RC beams that contain a higher percentage of steel bars at the tension zone and epoxy as a binder. Additionally, beams strengthened with 3-sides jacketing had the highest load capacities compared to the control, 1-side, and 2-side strengthened beams. Also, fiber-reinforced concrete that contains long steel fibers was more effective than short fibers for increasing load capacities. Finally, beams strengthened with the help of epoxy had higher flexural load capacity than the ones retrofitted by sandblasting or mechanical anchorages. On the other hand, strengthened beams had higher stiffness compared to the control specimens because the natural axis is coming down with the application of strengthening jackets. However, this improvement was more for the beams with a thicker layer of strengthening material, adding of steel fibers in the tension zone of the beams, and application of U-jacketing compared to the 1-side or 2-sides. The epoxy resin method reduced the displacement more than sandblasting because laminates act as rigid plates, and this was resulted to change the failure mode from flexural to brittle concrete cover separation. As a comparison, the beams strengthened with epoxy showed similar cracking patterns as the sandblasting technique, but cracking load capacity was higher due to the epoxy adhesive's higher tensile strength. Also, the beams strengthened by the epoxy glue method were stiffer compared to the mechanical anchorage and sandblasting. On the other hand, the initial stiffness of the repaired beams was a little lower than strengthened beams, and repaired beams had a lower load capacity compared to strengthened beams. Regarding the crack pattern, almost all the beams failed in flexure but with some differences. The control specimens failed in flexure, whereas the first cracks were initiated in the bottom portion of the beams, as the load was increased, more cracks were found and then widened between supports, followed by the reinforcement yielding and widening of flexural cracks in the flexural zone. The strengthened beams also failed in flexure and had similar trends but followed by separation, debonding, and rapture of the jackets or steel bars. As a comparison, it was observed that fewer cracks were visualized, while beams were strengthened in 3-sides and thicker layers compared to 1-layer or 2-sides due to the combination of side and bottom jackets, and the flexural cracks during failure were more concentrated to the mid-span. In addition, beams containing laminates failed in flexure with laminates fracture, but little difference in cracking initiation, number of cracks, and their locations were highlighted. Furthermore, for the beams retrofitted by epoxy resin, the failure mode was changed from flexure to brittle concrete cover separation without the failure of UHPFRC laminates because laminates act as rigid plates and resulting in decreased deflection. The cracking load was twice for the beams strengthened by UHPFRC jacketing compared to the control specimens and had delayed crack initiation and increased flexural load capacity as well. It was well summarized from analytical and FEM modeling that the experimental results were in good agreement with the analytical model and FEM findings. However, analytical and FEM results reported that beams were stiffer than experiments because experiment contains dry shrinkage, heat evolution during hydration, handling of RC beams that will cause micro-cracks, and finally, reduction in beams stiffness.

Table 2 indicates that the overall shear load capacity of RC beams has increased, as the beams were strengthened with any type of fiber-reinforced cementitious materials. As a comparison, 3-sides strengthened beams had the highest shear load capacity than 2-sides jacketing and beams only retrofitted at the bottom. In addition, the shear load capacity has improved for the beams strengthened by continuous strips compared to the beams with separate strips, using UHPFRC as a strengthening material instead of UHPC, FRCM, HPFRC, HS-SHCC, and etc, and using epoxy + bolt connection instead of the only epoxy. Furthermore, shear load capacity is enhanced by reducing stirrups spacing and increasing width of the beams, percentage of the longitudinal steel reinforcement, the volume fraction of steel fibers, and a thicker layer of the strengthened materials or adding bolts and increasing their numbers and diameter. Moreover, beams strengthened with the fiber-reinforced cementitious matrix containing short fibers, thicker epoxy layer, and high strength concrete had higher load capacity than beams strengthened with a matrix having long steel fibers, thinner jacketing layer, and low strength concrete, respectively. In addition, the improvement in shear load capacity was more notable for the beams having a greater shear span to effective depth ratio, a/d than specimens with a smaller a/d ratio. On the other hand, mid-span deflection and stiffness of the strengthened beams depend on the strength of strengthening materials and strengthening techniques. The 3-sides strengthened beams showed ductile behavior with fewer cracks than other configurations, therefore, a 3-sides strengthening configuration did not collapse suddenly and is mostly recommended for strengthening purposes. Moreover, mid-span deflection has increased with the increase of jacketing thickness, beam size, stirrups percentage, the volume fraction of steel fibers due to the high modulus of elasticity of the steel fibers, and usage of continuous strips instead of separate jackets because it provided higher strength and continuous confinement along the shear span. Besides, the beams strengthened with the epoxy mortar, and long steel fibers exhibited best ductile behavior and were effective in preventing RC beams from brittle failure. Furthermore, it was also observed that the strengthened beams did not collapse suddenly but showed some ductile behavior after failure as well. It was also observed that control beams failed mostly in pure and brittle shear that contains large diagonal shear cracks and less flexural cracks near to the mid-span, then the failure mode has been changed to the flexure for the strengthened beams. This proves the effectiveness of the strengthening materials to change brittle shear failures to the ductile flexure ones. In addition, the strengthened beams almost showed similar behavior as the control ones, whereas the first cracks were initiated in the middle of the specimens and such cracks were propagated deeper inside the beams. Thereafter, as the load was increased, diagonal cracks occurred at shear span, finally, the beams failed with widened mid-span cracks. Here

Table 1. Relative percentages of the flexural load capacity and mid-span deflection and cracking pattern of the RC beams strengthened with a different type of cementitious materials and studied by various authors.

Reference	Types of cementitious materials and method	Beam dimensions (B × H × L), mm	Strengthening configuration	Relative percentages		Crack pattern
				Ultimate load capacity	Ultimate mid-span deflection	
[35]	UHPFRC, shotcrete	150 × 200 × 2200	P1, and P2, control specimens	-	-	Flexure
			U1 and U2, strengthened with 50 mm thick and 150 mm widen UHPFRC layers at flexural side	+1.3	-13.3	Flexure crack + UHPFRC debonding
			UB1 and UB2, strengthened with UHPFRC layers and 2 ribbed 10 mm steel bars	+89.6	-22.2	Single flexural cracking + UHPFRC un-debonding
[31]	UHPFRC, sandblasting and epoxy	140 × 230 × 1600	RC-Control, control specimen	-	-	Pure Flexure
			RC-SB-BOTSJ, strengthened by sand blasting at bottom	+15.7	-19.8	Branching Flexure
			RC-SB-2SJ, strengthened by sand blasting at two sides	+45.7	-29.9	Pure Flexure
			RC-SB-3SJ, strengthened by sand blasting at three sides	+88.6	-76.2	Pure Flexure
			RC-EP-BOTSJ, strengthened by epoxy at bottom side	+7.1	-36.5	Branching Flexure
			RC-EP-2SJ, strengthened by epoxy at two sides	+35.7	-18.8	Pure Flexure
			RC-EP-3SJ, strengthened by epoxy at three sides	+84.3	-77.2	Pure Flexure

[36]	UHPFRC, high-pressure water-jet was performed to expose the aggregate	250 × 400 × 3000	BL-0, control specimens	-	-	Flexure with concrete crushing
			BU-20, strengthened at upper side with 20 mm thick UHPFRC layer	+19.6	-18.7	Flexure with UHPFRC crushing
			BU-40, strengthened at upper side with 40 mm thick UHPFRC layer	+24.6	-31.2	Flexure with rebar fracture
			BU-60, strengthened at upper side with 60 mm thick UHPFRC layer	+15.2	-37.5	-
			BL-20, strengthened at lower side with 20 mm thick UHPFRC layer	0.0	-46.8	Flexure with concrete crushing
			BL-40, strengthened at lower side with 40 mm thick UHPFRC layer	+22.2	-78.1	Flexure with rebar fracture
			BL-60, strengthened at lower side with 60 mm thick UHPFRC layer	+31.5	-75.0	Flexure with rebar fracture
[37]	UHPFRC, epoxy and mechanical anchoring	120 × 160 × 3200	Beam-1, control specimen	-	-	Flexure with concrete crushing
			Beam-2, strengthened by epoxy resin	+15.6	-13.7	Flexure with concrete crushing, no separation of laminates from UHPFRC
			Beam-3, strengthened by mechanical anchorage	+10.6	-28.3	Flexure while laminates broken to some parts
			Beam-4, strengthened by epoxy resin with added rebar	+118	-67.4	Flexure with concrete cover separation
			Beam-5, strengthened by mechanical anchorage with added rebar	+73.1	-5.2	Flexure while concrete at compressive part was crushed
[38]	Strengthening by HPFRC, sandblasting	300 × 500 × 4550	Control beam	-	-	flexure with debonding
			Beam strengthened by HPFRC but without steel bars	+35.8	-75.0	brittle collapsed with single crack at midspan
			RC beam strengthened by HPFRC	+115.8	-56.0	single crack near support with the rapture of longitudinal reinforcement
	Repairing by HPFRC, sandblasting		RC beam repaired by HPFRC	+92.1	-40.0	single crack near support
[39]	SHLSCC, manual chiseling with indentation of roughly	150 × 175 × 1500	Beam-Ref, control beam	-	-	Flexural
			Beam-H/H, half of the beam from normal concrete and half from SHLSCC	+33.1	-59.8	Flexural
			Beam-WC5, beam with pre-crack, and strengthened with 50 mm jacket	+14.4	-49.0	Flexural
			Beam-WOC5, beam without pre-crack, and strengthened with 50 mm jacket	+16.5	-57.0	Flexural
			Beam-WC6, beam with pre-crack, and strengthened with 60 mm jacket	+22.1	-78.3	Flexural
			Beam-WOC6, beam without pre-crack, and strengthened with 60 mm jacket	+27.5	-25.3	Flexural
			Beam-WC4, beam with pre-crack, and strengthened with 40 mm U-shaped jacket	+53.9	-86.3	Flexural
			Beam-WOC4, beam without pre-crack, and strengthened 40 mm U-shaped jacket	+57.9	-88.4	Flexural
[40]	HDC and RPC, chipping the concrete to a certain depth	150 × 200 × 2400	CB1, control beam with 0.81% of longitudinal reinforcement	-	-	Failure with the yield of longitudinal reinforcement, followed by the extension of cracks to the compression zone and concrete crushing
			CB2, control beam with 1.83% of longitudinal reinforcement	+96.8	-20.0	
			CB3, control beam with 2.46% of longitudinal reinforcement	+144.8	-61.3	
			HT1, beam strengthened by HDC at the tension zone and containing 0.81% of longitudinal reinforcement	+170.8	-45.7	Failure with the yield of longitudinal reinforcement at HDC layer and then normal concrete, followed by concrete crushing at the compression zone
			HT2, beam strengthened by HDC at the tension zone and containing 1.83% of longitudinal reinforcement	+86.2	-41.7	
			HT3, beam strengthened by HDC at the tension zone and containing 2.46% of longitudinal reinforcement	+65.1	+42.6	
			HC1, beam strengthened by HDC at the compression zone and containing 0.81% of longitudinal reinforcement	+10.4	+134.9	Failure with less horizontal cracks followed by concrete crushing and debonding between HDC and host concrete
			HC2, beam strengthened by HDC at the compression zone and containing 1.83% of longitudinal reinforcement	+9.0	+62.3	
			HC3, beam strengthened by HDC at the compression zone and containing 2.46% of longitudinal reinforcement	+7.2	+235.2	
			RC1, beam strengthened by RPC at the compression zone and containing 0.81% of longitudinal reinforcement	+22.9	+175.2	Failure with less horizontal cracks followed by concrete crushing and good bond between RPC and host concrete
			RC2, beam strengthened by RPC at the compression zone and containing 1.83% of longitudinal reinforcement	+10.0	+55.1	
			RC3, beam strengthened by RPC at the compression zone and containing 2.46% of longitudinal reinforcement	+11.5	-13.3	
[41]	ECC+BFRP	200 × 300 × 1800	BB0, control beam	-	-	Flexure with concrete crushing
			BB1-1, strengthened with 30 mm ECC+1 mm BFRP	+3.9	-60.1	Flexure with rupture of BFRP and concrete crushing
			BB1-3, strengthened with 30 mm ECC+3 mm BFRP	+15.8	-59.4	Flexure with rupture of BFRP and concrete crushing
			BB1-5, strengthened with 30 mm ECC+5 mm BFRP	+32.5	-59.3	Flexure with debonding of BFRP and concrete crushing

[42]	UHPFRC, UHPC, CRM, NSC, crack were grooved in V-shape, then water is sprinkled to remove loose particles	150 × 200 × 1100	Control beams	-	-	Flexure with more widen and long cracks
			Beams repaired with UHPFRC	+18.0	-28.4	Flexure with less widen and short cracks
			Beams repaired with UHPC	+7.0	-19.8	Flexure with less widen and short cracks
			Beams repaired with CRM	+11.0	-30.8	Flexure with less widen and short cracks
			Beams repaired with NSC	-4.0	-4.7	Flexure with more widen and long cracks
[43]	HPFRC, epoxy	100 × 150 × 1100	Control beams	-	-	Shear or shear-flexure
			Beams strengthened with 16 mm thick HPFRC layer at bottom only	+9.0	-24.1	Flexure
			Beams strengthened with 20 mm thick HPFRC layer at bottom only	+18.0	-56.3	Shear-flexure
			Beams strengthened with 16 mm thick HPFRC layer at bottom and sides	+26.0	-70.7	Flexure
			Beams strengthened with 20 mm thick HPFRC layer at bottom and sides	+18.6	-	Flexure
			Beams strengthened with 16 mm thick HPFRC layer with U-strips	+66.3	-86.4	Flexure
			Beams strengthened with 20 mm thick HPFRC layer with U-strips	+102.0	-88.6	Flexure
			Beams strengthened with 20 mm thick HPFRC layer at bottom and sides (Mix II)	+22.7	-	Flexure

Minus (-) and plus (+) signs represent a decrease and increase in the structural behaviors of RC beams calculated regarding the reference specimens of each study, respectively

Table 2. Relative percentages of shear load capacity, mid-span deflection and crack pattern of the RC beams strengthened with different types of cementitious materials and studied by various authors.

Reference	Types of cementitious materials and methods	Beam dimensions (BxHxL), mm	Strengthening configuration	Relative percentages		Crack pattern
				Ultimate load capacity	Ultimate mid-span deflection	
[48]	UHPC, sandblasting	140 × 230 × 1120	CT-1.0, control specimens with *a/d=1.0*	-	-	Shear
		200 × 230 × 1120	SB-2SJ-1.0, strengthened beam with 2-side jacketing and contains *a/d=1.0*	+48.0	+105.2	Flexure + shear
		200 × 260 × 1120	SB-3SJ-1.0, strengthened beam with 3-side jacketing and contains *a/d=1.0*	+64.0	+68.3	Flexure
		140 × 230 × 1120	CT-1.5, control specimens with *a/d=1.5*	-25.3	+169.9	Shear
		200 × 230 × 1120	SB-2SJ-1.5, strengthened beam with 2-side jacketing and contains *a/d=1.5*	+5.0	+259.8	Flexure + shear
		200 × 260 × 1120	SB-3SJ-1.5, strengthened beam with 3-side jacketing and contains *a/d=1.5*	+25.8	+381.1	Flexure
		140 × 230 × 1120	CT-2.0, control specimens with *a/d=2.0*	-27.9	+248.6	Shear
		200 × 230 × 1120	SB-2SJ-2.0, strengthened beam with 2-side jacketing and contains *a/d=2.0*	-9.7	+388.0	Flexure + shear
		200 × 260 × 1120	SB-3SJ-2.0, strengthened beam with 3-side jacketing and contains *a/d=2.0*	-7.8	+392.4	Flexure
[49]	UHPFRC, epoxy	150 × 300 × 2000	C-S, control specimen	-	-	Brittle shear
			C-F, control specimen but with more stirrups than C-S	+120.0	+175.0	Flexure
		210 × 300 × 2000	C-S-210, control specimen with wider cross-section	+84.0	+53.3	Brittle shear
		150 × 300 × 2000	ST-1S, beams strengthened at one side with 60 mm UHPFRC jackets	+145.0	+75.0	Shear cracks, appeared along the non-strengthened side with flexural cracks and UHPFRC debonding
			ST-1S-R, beams strengthened at one side with 60 mm UHPFRC jackets and reinforced with extra bars as well	+34.0	+61.7	Flexural cracks on the strengthened side, while shear crack appeared in un-strengthened side
			ST-2S, beams strengthened at 2-side with 30 mm UHPFRC jackets	+188	+66.7	Shear failure with UHPFRC rupture
			ST-2S-R, beams strengthened at 2-side with 300 mm UHPFRC jackets and reinforced with extra bars as well	+120	+100.0	Flexure
[50]	HPFRC, sandblasting	200 × 450 × 2850	Un-reinforced control beam	-	-	Shear
			Beam-B, was strengthened with 50 mm HPFRC jackets of self levelling materials at lateral and lower sides	+71.8	+74.35	Flexural with bending mechanics
			Beam-D was strengthened with 50 mm jackets at three sides but thixotropic material with epoxy bonding was considered for lateral faces	+64.7	+48.7	Flexural with bending mechanics
			Beam-E was strengthened with 50 mm jackets at lower side and 30 mm thixotropic material for lateral faces	+48.9	+77.0	Flexural with bending mechanics
[51]	UFC (quarter size beams), epoxy	150 × 240 × 1500	Control specimen	-	-	Shear compression failure
			Beam strengthened with UFC in the shear spans	+40.0	+400.0	UFC panel peeling failure
	UFC (half size beams), epoxy	300 × 500 × 1500	Control specimen	-	-	Diagonal tension failure
			Beam strengthened with 14 mm thick UFC layer in the shear spans	+45.4	+57.1	Shear compression failure
			Beam strengthened with 28 mm thick UFC layer in the shear spans	+52.2	+60.7	Flexural failure

[52]	Epoxy mortar with steel fibers (EMSF)	250 × 400 × 2400	E0, control specimen	-	-	Shear failure
			EP, beam strengthened with epoxy mortar	+167.0	+96.0	brittle shear failure
			EPSF-1S, beam strengthened with 7.5 mm thick layer of epoxy mortar + short steel fibers	+215.0	+97.0	Shear failure with concrete debonding
			EPSF-2S, beam strengthened with 12.5 mm thick layer of epoxy mortar + short steel fibers	+284.0	+117.0	Shear failure with concrete debonding
			EPSF-1H, beam strengthened with 7.5 mm thick layer of epoxy mortar + short steel fibers and long steel fibers	+267.0	+133.0	Shear failure with ductile behavior
			EPSF-2H, beam strengthened with 12.5 mm thick layer of epoxy mortar + short steel fibers and long steel fibers	+257.0	+137.0	Shear failure with ductile behavior
[53]	HS-SHCC, roughened concrete surface	180 × 350 × 2100	R, control beam (S/D=1.5:1)	-	-	Shear crack with large diagonal shear cracks and less flexural cracks near to the mid-span
			S, strengthened with 10 mm SHCC at the both sides (S/D=1.5:1)	+13.9	-11.9	
			R, control beam (S/D=2.5:1)	-41.6	-6.8	Large shear crack with minor detachment between RC beams and SHCC and no spalling
			S, strengthened with 10 mm SHCC at the both sides (S/D=2.5:1)	-30.6	+17.0	
[54]	FRCM, the concrete surface, dust and loose particles were removed by compressed-air cleaning	152 × 306 × 1829	L_0_Ave, control beam and strengthened by FRCM that contains lower compressive strength	-	-	Compression shear failure
			L_1_Ave, beam strengthened by one ply of FRCM that contains lower compressive strength	+21.7	+46.3	Compression shear failure and with cracks reflecting into FRCM and visible fiber strands slip
			L_4_Ave, beam strengthened by 4 plies of FRCM that contains lower compressive strength	+50.5	+47.0	Shear crack inclined at an angle of about 45° towards the point of load application and the failure was due to the partial delamination of the FRCM
			H_0_Ave, control beam and strengthened by FRCM that contains high compressive strength	+9.8	+3.1	Compression shear failure
			H_1_Ave, beam strengthened by one ply of FRCM that contains higher compressive strength	+38.5	+23.2	Compression shear failure and with cracks reflecting into FRCM and visible fiber strands slip
			H_4_Ave, beam strengthened by 4 plies of FRCM that contains higher compressive strength	+77.2	+24.6	Shear crack inclined at an angle of about 45° towards the point of load application and the failure was due to the partial delamination of the FRCM
[55]	PBO-FRCM, sandblasting	203 × 305 × 2133	BA-C, control beam with stirrups	-	-	Shear crack with the initiation of a single diagonal crack in shear spans
			BA-S-1, beam strengthened with one ply of 102 mm strips at 204 mm spacing and with stirrups	+18.2	+44.4	Diagonal shear crack but followed by slippage or rupture of FRCM
			BA-S-4, beam strengthened with 4 plies of 102 mm strips at 204 mm spacing and with stirrups	+18.2	+33.3	Diagonal shear crack but followed by slippage or rupture of FRCM
			BA-C-1, beam strengthened with one ply of 560 mm continuous strips and with stirrups	+23.1	+77.8	Shear-flexure cracks, whereas shear cracks were initiated and the internal shear reinforcement yielded
			BA-C-4, beam strengthened with 4 plies of 560 mm continuous strips and with stirrups	+31.4	+88.9	Shear-flexure cracks, whereas shear cracks were initiated and the internal shear reinforcement yielded
			BB-C, control beam without stirrups	-31.4	+11.1	Single diagonal tensile crack in shear spans
			BB-S-1, beam strengthened with one ply of 102 mm strips at 204 mm spacing and without stirrups	-11.2	-20.0	Single diagonal tensile crack in shear spans with a slippage of PBO
			BB-S-4, beam strengthened with 4 plies of 102 mm strips at 204 mm spacing and without stirrups	+3.6	-10.0	Single diagonal tensile crack in shear spans with no shear failure through the PBO-FRCM strengthening system
			BB-C-1, beam strengthened with one ply of 560 mm continuous strips and without stirrups	+21.1	0	Single diagonal tensile crack in shear spans
			BB-C-4, beam strengthened with 4 plies of 560 mm continuous strips and without stirrups	+6.7	-40.0	Single diagonal tensile crack in shear spans with a slippage of PBO with no shear failure through the PBO-FRCM strengthening system

[22]	Steel fiber-reinforced concrete panels (SFRC), epoxy	150 × 300 × 1800	Control beam	-	-	Diagonal tension failure
			1.5F-epoxy, beam strengthened by SFRC containing 1.5% of steel fibers with the help of only epoxy	+90.6	+188.9	shear failure of with the debonding of the SFRC panel
			0F-8D12, beam strengthened by SFRC containing 0% of steel fibers and 8 × 12 mm bolts with the help of only epoxy + bolts	+90.0	+171.1	Diagonal shear failure with more cracks in the mortar panel
			1F-8D12, beam strengthened by SFRC containing 1.0% of steel fibers and 8 × 12 mm bolts with the help of only epoxy + bolts	+84.7	-13.3	Diagonal shear failure with less cracks in the mortar panel and no debonding of SFRC panels
			1.5F-8D12, beam strengthened by SFRC containing 1.5% of steel fibers and 8 × 12 mm bolts with the help of only epoxy + bolts	+105.4	+84.4	
			1.5F-4D12, beam strengthened by SFRC containing 1.5% of steel fibers and 4 × 12 mm bolts with the help of only epoxy + bolts	+102.0	+17.8	
			1.5F-6D12, beam strengthened by SFRC containing 1.5% of steel fibers and 6 × 12 mm bolts with the help of only epoxy + bolts	+87.1	+48.9	
			1.5F-6D10, beam strengthened by SFRC containing 1.5% of steel fibers and 6 × 10 mm bolts with the help of only epoxy + bolts	+86.5	+148.9	
			1.5F-8D10, beam strengthened by SFRC containing 1.5% of steel fibers and 8 × 10 mm bolts with the help of only epoxy + bolts	+100.9	+40.0	

Minus (-) and plus (+) signs represent a decrease and increase in the structural behaviors of RC beams calculated regarding to the reference specimens of each study, respectively.

Table 3. Relative percentages of the torsional capacity, angle of twist, and cracking pattern of the RC beams strengthened by different types of cementitious materials and studied by various authors.

Reference	Types of cementitious materials and methods	Beam dimensions (BxHxL), mm	Strengthening configuration	Relative percentages		Crack pattern
				Ultimate torque capacity	Ultimate twist angle	
[9]	UHPC, sandblasting	100 × 200 × 1600	RS-S00, control beam	-	-	Pure torsion
			RS-S00-F25, fully wrapped with 25 mm thick jackets	+267	+427	Pure torsion
			RS-S00-F20, fully wrapped with 20 mm thick jackets	+210	+191	Pure torsion
			RS-S00-F15, fully wrapped with 15 mm thick jackets	+187	+164	Pure torsion
			RS-S00-F10, fully wrapped with 10 mm thick jackets	+152	+145	Pure torsion
			RS-S00-F25, U-jacketing (3-side) with 25 mm thick jackets	+195	+109	Pure torsion due to the formation of the single spiral crack, followed by de-bonding between the interface of RC beams and UHPC
			RS-S00-F20, U-jacketing (3-side) with 20 mm thick jackets	+158	+91	
			RS-S00-F15, U-jacketing (3-side) with 15 mm thick jackets	+127	+73	
			RS-S00-F10, U-jacketing (3-side) with 10 mm thick jackets	+107	+73	
			RS-S00-LR25, left and right jacketing (2-side) with 25 mm thick jackets	+82	+64	
			RS-S00-LR15, left and right jacketing (2-side) with 15 mm thick jackets	+65	+64	
[59]	PBO-FRCM, sandblasting	203.2 × 304.8 × 2133.6	Control beam	-	-	Typical torsional behavior with spiral diagonal cracks around the cross-section of the beam
			N-P-3-S-1, 3-side configuration of FRCM at 101.6 mm spacing and 101.6 mm thickness	+8	-11	Failure occurred near beams restrained end and followed by concrete cover spalling.
			N-P-4-S-1, 4-side configuration of FRCM at 101.6 mm spacing and 101.6 mm thickness	+30	+188	Failure due to fiber rapture followed by concrete crushing and loss of confinement at the mid-span.
			N-P-4-C-1, completely fully wrapped without spacing and one layer of jacketing	+62	+171	
			N-P-4-C-2, completely fully wrapped without spacing and two layer of jacketing	+109	+184	
[60]	HPFRC mortar	3000 mm length, (300 × 300) mm complete cross-section, and (200 × 200) mm cross-section of the core	BN21 were containing 21 MPa concrete in the whole section	-	-	Skew-bending-type of failure and more cracks, which were connected to the large cracks in the beams
			BN40 were containing 40 MPa concrete in the whole section	+32.3	+21.4	
			BF1.5 were consisting of 21 MPa concrete in the core and covered with the HPFRC layer that contains 1.5% polyvinyl alcohol (PVA) fibers	+30.8	-57.1	Skew-bending-type of failure and less cracks, which were not connected to the large cracks in the beams
			BF2.0 were consisting of 21 MPa concrete in the core and covered with the HPFRC layer that contains 2.0% polyvinyl alcohol (PVA) fibers	+43.8	-28.6	

Minus (-) and plus (+) signs represent a decrease and increase in the structural behaviors of the RC beams calculated regarding the reference specimens of each study, respectively

the beams did not collapse suddenly but showed some ductile behavior after failure as well. However, as the load was approaching to the ultimate, minor detachment or debonding were found between RC beams and strengthening jackets or slippage/rupture occurred in jacketing layers, but this debonding can be eliminated with the introduction of steel bars or using epoxy + bolt connection instead of the only epoxy as an adhesive material. In addition, a high number of cracks were visible for the beams strengthened by concrete without and a lower percentage of steel fiber due to lower tensile strength of the strengthening materials and number of the cracks has been decreased with the increase of volume fraction of steel fibers because the fibers make bridges in the strengthening materials. Finally, it was observed form nonlinear FEM results that shear behaviors of the strengthened RC beams such as; load capacity, stiffness, deflection, load-deflection curve, and cracking pattern predicted by FEM software were in good agreement with the experimental results.

Table 3 summarizes the torsional behaviors of the RC beams strengthened by different cementitious materials. It has been well documented from the literature that less research work is conducted to compromise the data concerning this important property of the RC beams. However, all authors were agreed and obtained similar results, which was a significant improvement in both torsional load capacities and the twisting angle for the strengthened beams as compared to the reference ones. As a comparison, torsional load capacity and twisting angle of the strengthened beams were much improved for fully wrapped beams and strengthened by a thicker layer of fiber-reinforced cementitious materials compared to the 1-layer, 2-sides, and 3-sides configurations, and a thinner layer of cementitious materials, respectively. Therefore, it is recommended to apply fully wrapping with a thicker layer of cementitious materials to achieve much improved torsional properties. Moreover, the torsional load capacity has improved for the beams containing high strength concrete and with the increase of percentage of steel fibers in the strengthening materials. In addition, the existence of transverse reinforcement had a considerable effect on both torsional load capacity and twisting angle, where both values were enhanced for the beams containing a higher amount of stirrups. Regarding the cracking pattern, it was reported that the control beam has more cracks and a faster rate of crack development compared to the strengthened beams, where debonding of fibers rupture were noticed between the RC beam interfaces and the jackets of the strengthening materials. In general, before cracking the strengthened beams showed a linear behavior with high stiffness. Thereafter, the twisting angle enhanced without the increase of torque capacity due to the redistribution of forces from concrete to the steel bars. Lastly, beams suffered non-linear behavior with a reduction of stiffness before they reached the peak load.

Conclusions and Recommendations

The following points are summarized from the previously explained literature concerning the structural behaviors of RC beams strengthened by various types of fiber-reinforced cementitious materials and methods:

- Fiber-reinforced cementitious materials with the help of epoxy resin, sandblasting, shotcrete, or other methods have the perfect bonds with the host concrete. In addition, it was documented that the ultra-high performance fiber reinforced concrete (UHPFRC) with a high volume fraction of steel fibers was the most effective material than other types of fiber-reinforced cementitious materials for strengthening/repairing purposes. In addition, epoxy was confirmed as the most suitable adhesive materials than sandblasting, mechanical anchorage or others, while epoxy + bolting was the best connection technique to strengthened RC beams.
- Shear or flexural load capacities have increased remarkably for the beams strengthened by fiber-reinforced cementitious materials and this enhancement was more remarkable for the beams strengthened by 3-sides configuration compared to other retrofitting methods. Moreover, the beams strengthened by continuous strips or retrofitted in the tension zone had higher load capacity than beams having the spaced strips and strengthened in the compression zone, respectively. In addition, flexural and shear load capacities were strongly related and directly proportional to the thickness of the materials, number of the layers, strength of the bonding materials, longitudinal reinforcement ratio, volume fraction of steel fibers, strength of the concrete, beam size, and value of a/d ratio.
- While studying beams in flexure, almost all the strengthened beams had higher stiffness than the control ones because the natural axis is coming down with the introduction of retrofitting jackets. However, this enhancement was weightier for the beams strengthened with a thicker layer and U-jacketing of fiber-reinforced cementitious materials and using epoxy as adhesive materials. Moving to the crack pattern, almost all the beams failed in flexure. The control beams started with the first cracks at the bottom and then widened between supports, followed by the reinforcement yielding and flexural failure in the flexural zones. While, the strengthened beams failed in flexure as well and had similar trends as the control specimens, but followed by separation, debonding, and rapture of the jackets or steel bars. Moreover, fewer cracks were observed for the beams strengthened in 3-sides with a continuous and thicker layer of the strengthened materials, and the flexural cracks during failure were more concentrated to the mid-span.
- The mid-span deflection of the shear-strengthened beams improved remarkably than the control ones. However, the increase in mid-span deflection was more significant and directly related to the numbers and thickness of jacketing, beam size, shear reinforcement ratio, percentage of steel fibers due to its high modulus of elasticity, and etc. Furthermore, attachment of the continuous strips was more effective than spaced jackets because it provides higher strength and continuous confinement along the shear span, use of epoxy and long steel fibers that displayed superlative ductile behavior and were preventing RC beams from brittle failure. On the other hand, the majority of the control beams failed in pure and brittle shear that contains widened diagonal shear cracks and less flexural cracks near to the mid-span. While for the strengthened beams, the failure mode has been changed from the brittle shear to the ductile flexure, which verifies the effectiveness of the strengthening materials. However, the strengthened beams have experienced minor detachment or debonding between RC beams and the strengthening jackets or slippage/rupture occurred in jacketing layers. In addition, it was observed that the debonding could be eliminated with the introduction of steel bars or using epoxy + bolt connection.
- The torsional strength and twisting angle of the RC beams strengthened by different fiber-reinforced cementitious materials have improved significantly compared to the reference ones. This improvement was more remarkable for the fully wrapped beams compared to the 1-layer, 2-sides, and 3-sides configurations. In addition, beams strengthened with a thicker layer of fiber-reinforced materials, the strengthening materials with a high amount of steel fibers, concrete with high strength, and a high ratio of stirrups had enhanced torsional behaviors. Regarding the cracking pattern, it was reported that the control beam had more cracks and a faster rate of cracks development compared to the strengthened beams, while debonding or fibers rupture were noticed between the RC beam interfaces and jackets of the strengthening materials.
- Overall, the FEM results were in good agreement with the experimental findings. However, in some cases analytical and finite element methods represent somewhat stiffer behaviors than the experiments. This is attributed from the fact that the experiment involves dry shrinkage, heat evolution during hydration, and handling of RC beams that causes micro-cracks, while analytical and FEM do not include such micro-cracks.

Perspectives and recommendations for future work

It was observed from the previous research works that a large number of research investigations have been performed to study the structural behaviors of the RC beams retrofitted/repaired by different types of fiber-reinforced cementitious materials and various configurations. However, lots of information still remains unidentified that needs additional investigation and opens a window for future researchers.

- The shear span to effective depth ratio, a/d, fibers percentages, types, shape and orientation, and anchorage conditions have a great effect on both load capacities and displacements/rotation of the RC beams. Therefore, further investigations are needed to consider the effect of such parameters in the strengthened beams.

- The bonding between fiber-reinforced cementitious materials and the host concrete was effective but in some cases a small values of slip at the interface were recorded. Therefore, intensive research works are required to explore the interface characteristics between strengthening materials and the host concrete.
- Comprehensive, updated, and full design guidelines, code of practice, recommendations are required to ensure more rapid and effective applications of fiber-reinforced cementitious materials for the strengthening of structural elements.
- The above literature has summarized that a large variation between test results was reported due to differences in tested specimens, material types, test arrangement, loading configurations, and etc. Therefore, research work is required to develop a standardized testing method and procedure that will cover weather conditions, test duration, specimens' shapes, and sizes, loading type and configuration, and etc.

Proposed methods and materials

After careful consideration and review of the previous research work, the authors recommend and propose the following retrofitting configurations and materials:

- It was found that the ultra-high performance fiber-reinforced concrete (UHPFRC) and epoxy have greatly enhanced the flexural, shear, and torsional properties, which are strongly proposing to strengthen/repair the RC beams.
- A combination of two configurations is proposed for the flexural strengthening; 1) at shear spans, the inclined strips in both faces and opposite direction of the diagonal cracks initiation, and 2) at flexural zones, full wrapping. Since in flexural loading, generally, the beam will fail in flexural zones, where full wrapping will delay the crack initiation and improve the flexural load capacity, stiffness, and decrease width and depth of the cracks. If the crack pattern will be changed from flexure to shear zones the inclined strips will work effectively.
- For shear strengthening, the switched method as was proposed for the flexural strengthening is suggested; 1) at shear zones, full wrapping, and 2) at flexural parts, the inclined strips in both faces. During shear loading, the beams are commonly designed to fail in shear spans, here, full wrapping will strengthen those portions effectively and will delay the crack initiation and improve shear behaviors of the RC beams. On the other hand, if the failure will happen in flexural zones, the inclined strips will effectively take responsibility.
- In the torsional retrofitting, full wrapping of complete beams is strongly recommended, as there are possibilities for the initiation of torsional cracks on any part of the beams. Such configuration could enhance both torsional load capacity and twisting angle and delay the initiation of the cracks.

Acknowledgements

Thanks to the technical staffs of both laboratories in France and Afghanistan for their help and support.

Declaration of Interests

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

References

1. Nilson, Arthur H, David Darwin and Charles Dolan. "Design of concrete structures" *McGrow-Hill Companies Inc* (2010).
2. McCormac, Jack and Russell H Brown. "Design of Reinforced Concrete" *John Wiley & Sons Inc* (2006).
3. K Wight, James and James G. Macgregor. "Reinforced concrete mechanics & design" *Pearson Education Inc* (2012).
4. https://doi.org/10.1016/0950-0618(94)90003-5 .
5. Emmons Peter H. "Concrete Repair and Maintenance Illustrated: Problem Analysis" *Repair Strategy; Techniques* 28 (1992).
6. https://doi.org/https://doi.org/10.1002/app.2263 .
7. https://doi.org/10.1139/l00-031 .
8. https://doi.org/10.2749/101686613X13627347100437 .
9. https://doi.org/10.1016/j.conbuildmat.2015.12.160.
10. Graybeal, Benjamin A and Florent Baby, "Development of Direct Tension Test Method for Ultra-High-Performance Fiber-Reinforced Concrete" *Materials Journal*. 110 (2013): 177-186.
11. Tai, YS, HH Pan and YN Kung. "Mechanical properties of steel fiber reinforced reactive powder concrete following exposure to high temperature reaching 800 °c, Nuclear Engineering and Design" 241 (2011): 2416-2424.
12. Rahman, S, T Molyneaux and I Patnaikuni. "Ultra high performance concrete: recent applications and research" *Australian Journal of Civil Engineering* 2 (2005): 13-20.
13. Henry G Russel and Graybeal Benjamin A. "Ultra-High Performance Concrete : A State-of-the-Art Report for the Bridge Community" *Infrastructure Research and Development* (2013).
14. https://doi.org/10.1016/j.compositesb.2014.08.001 .
15. Meng, Weina and Kamal H Khayat. "Experimental and Numerical Studies on Flexural Behavior of Ultrahigh-Performance Concrete Panels Reinforced with Embedded Glass Fiber-Reinforced Polymer Grids" *Journal of the Transportation Research Board* 2592 (2016): 38-44.
16. Yaghoob, Farnam, Soheil Mohammadi and Mohammad Shekarchi. "Experimental and numerical investigations of low velocity impact behavior of high-performance fiber-reinforced cement based composite" *International Journal of Impact Engineering* 37 (2010): 220-229.
17. Hallaq, AL, Ahmed Tayeh, Bassam A Shihada and Samir. "Investigation of the Bond Strength Between Existing Concrete Substrate and UHPC as a Repair Material" *International Journal of Engineering and Advanced Technology* 6 (2017): 210-217.
18. Yin, Hor, Wee Teo and Kazutaka Shirai. "Experimental investigation on the behaviour of reinforced concrete slabs strengthened with ultra-high performance concrete" *Construction and Building Materials* 155 (2017): 463-474.
19. Lampropoulos, Andreas, SA Paschalis, OT Tsioulou and SE Dritsos. "Strengthening of Reinforced Concrete Beams using Ultra High Performance Fibre Reinforced Concrete" *Concrete Repair, Rehabilitation and Retrofitting* (ICCRRR2015) (2015).
20. Zhu, Yanping, Yang Zhang, Husam H Husseina and Genda Chen. "Flexural strengthening of reinforced concrete beams or slabs using ultra-high performance concrete (UHPC): A state of the art review" *Engineering Structures* 205 (2020): 110035.
21. Shriram, J, Sreenath S and Saravana Raja Mohan K. "Strengthening of Reinforced Concrete Beams Using Engineered Cementitious Composites" *International Journal of Civil Engineering and Technology* 9 (2018): 608-613.
22. Jongvivatsakul, Pitcha, Linh VH Bui, Theethawachr Koyekaewphring and Atichon Kunawisarut, et al. "Using Steel Fiber-Reinforced Concrete Precast Panels for Strengthening in Shear of Beams: An Experimental and Analytical Investigation" *Advances in Civil Engineering* 2019 (2019): 18.
23. Bahij, Sifatullah, Saheed K Adekunle, Mohammed Al-Osta, Shamsad Ahmad. "Numerical investigation of the shear behavior of reinforced ultra-high-performance concrete beams" *Structural Concrete* (2017): 1-13.
24. Katzer, Jacek. "Steel Fibers and Steel Fiber Reinforced Concrete in Civil Engineering" *The Pacific Journal of Science and Technology* 7 (2006): 53-58.
25. Maidl, Bernhard R and Jörg Dietrich. "Steel fibre reinforced concrete" *Berlin: Ernst & Sohn* (1995).

26. Fehling, Ekkehard, Michael Schmidt, Joost Walraven and Torsten Leutbecher. "Ultra-High Performance Concrete (UHPC) Fundamentals, Design, Examples" *John Wiley & Sons* (2014).

27. Graybeal, Benjamin Allen. "Characterization of the behavior of ultra-high performance concrete (Doctoral dissertation)" *Civil & Environmental Engineering Theses and Dissertations* (2005).

28. Ahmad, S, S Bahij, M Al-Osta and Al-Saheed, et al. "Shear Behavior of Ultra-High-Performance Concrete (UHPC) Beams Reinforced with High-Strength Steel Bars" *Structural Journal* 116 (2019): 3-14.

29. Błaszczyńskia, Tomasz and Marta Przybylska-Fałek. "Steel fibre reinforced concrete as a structural material" *Procedia Engineering* 122 (2015): 282-289.

30. Perry, VH and D Zakariasen. "First Use of Ultra-High Performance Concrete for an Innovative Train Station Canopy" *Concrete Technology Today* 25 (2004): 1-2.

31. Al-Osta, MA, MN Isa, MH Baluch and MK Rahman. "Flexural behavior of reinforced concrete beams strengthened with ultra-high performance fiber reinforced concrete" *Construction and Building Materials* 134 (2017): 279-296.

32. Tayeh, Bassam A, BH Abu Bakar, MA Megat Johari and Yen Lei Voo. "Utilization of ultra-high performance fibre concrete (UHPFC) for rehabilitation a review" *Procedia Engineering* 54 (2013): 525-538.

33. Bae, Baek-Il, Hyun-Ki Choi and Chang-Sik Choi. "Flexural Strength Evaluation of Reinforced Concrete Members with Ultra High Performance Concrete" *Advances in Materials Science and Engineering* 2016 (2016).

34. Ashby, Michael F and D Cebon. "Materials selection in mechanical design" *Journal De Physique* 3 (1993).

35. Paschalis, Spyridon A, Andreas P Lampropoulos and Ourania Tsioulou. "Experimental and numerical study of the performance of ultra high performance fiber reinforced concrete for the flexural strengthening of full scale reinforced concrete members" *Construction and Building Materials* 186 (2018): 351-366.

36. Safdar, Muhammad, Takashi Matsumoto and Ko Kakuma. "Flexural behavior of reinforced concrete beams repaired with ultra-high performance fiber reinforced concrete (UHPFRC)" *Composite Structures* 157 (2016): 448-460.

37. Tanarslan, HM, N Alver, R Jahangiri, Ç Yalçınkaya, et al. "Flexural strengthening of RC beams using UHPFRC laminates : Bonding techniques and rebar addition" *Construction and Building Materials* 155 (2017): 45-55.

38. Martinola, Giovanni, Alberto Meda, Giovanni A Plizzari and Zila Rinaldi. "Strengthening and repair of RC beams with fiber reinforced concrete" *Cement and Concrete Composites* 32 (2010): 731-739.

39. Iqbal, Shahid, Ahsan Ali, Klaus Holschemacher and Thomas A. Bier, et al. "Strengthening of RC beams using steel fi ber reinforced high strength lightweight self-compacting concrete (SHLSCC) and their strength predictions, *Materials and Design* 100 (2016): 37-46.

40. Deng, Mingke, Fudong Ma, Wang Ye and Fangyuan Li. "Flexural behavior of reinforced concrete beams strengthened by HDC and RPC" *Construction and Building Materials* 188 (2018): 995-1006.

41. Wang, W and Y Zheng. "Flexural Strengthening Rc Beams Using a Composite Reinforcement Layer: FRP Grid and ECC, The 12th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-12) & The 5th Asia-Pacific Conference on Fiber Reinforced Polymers in Structures (APFIS-2015)" *Joint Conference* (2015): 14-16.

42. Shihada, Samir M and Yasser M Oida. "Repair of Pre-Cracked RC Beams Using Diffent Cementitious Materials" *Journal of Sientific Research & Reports* 2 (2013): 655-664.

43. Alaee, Farshid Jandaghi and Bhushan Lal Karihaloo. "Retrofitting of reinforced concrete beams with CARDIFRC" *Journal of Composites for Construction* 7 (2003): 174-186.

44. Holschemacher, Klaus, Shahid Iqbal, Ahsan Ali and Thomas A Bier. "Strengthening of RC beams using lightweight self-compacting cementitious composite" *Procedia Engineering* 172 (2017): 369-376.

45. Ombres, Luciano. "Flexural analysis of reinforced concrete beams strengthened with a cement based high strength composite material" *Composite Structures* 94 (2011): 143-155.

46. Prem, Prabhat Ranjan and A. RamachandraMurthy. "Acoustic emission and flexural behaviour of RC beams strengthened with UHPC overlay" *Construction and Building Materials* 123 (2016): 481-492.

47. Lampropoulos AP, SA Paschalis, OT Tsioulou and SE Dritsos. "Strengthening of reinforced concrete beams using ultra high performance fibre reinforced concrete (UHPFRC)" *Engineering Structures* 106 (2016): 370-384.

48. Bahraq, Ashraf Awadh, Mohammed Ali Al-Osta, Shamsad Ahmad and Mesfer Mohammad Al-Zahrani. "Experimental and Numerical Investigation of Shear Behavior of RC Beams Strengthened by Ultra - High Performance Concrete" *International Journal of Concrete Structures and Materials* 13 (2019): 6.

49. Sakr, Mohammed A, Ayman A Sleemah, Tarek M Khalifa and Walid N Mansour. "Shear strengthening of reinforced concrete beams using prefabricated ultra-high performance fiber reinforced concrete plates: Experimental and numerical investigation" *Structural Concrete* 20 (2019): 1-17.

50. Mostosi, Serena, Alberto Meda, Paolo Riva and Stefano Maringoni. "Shear Strengthening of RC Beams with High Performance Jacket" *Concrete Engineering for Excellence and Efficiency* (2011).

51. Wang, Jian, Hidenori Morikawa, and Tetsuo Kawaguchi. "Shear strengthening of RC beams using ultra-high-strength fibre- reinforced concrete panels" *Magazine of Concrete Research* 67 (2015): 718-729.

52. Lee, KS, SH Lee and SW Shin, "Shear Behavior of Reinforced Concrete Beams Strengthened by Epoxy Mortar Panel with Steel Fibers" *Advances in Structural Engineering* 16 (2013): 987-999.

53. https://doi.org/10.21012/fc10.233281

54. Loreto, Giovanni, Saman Babaeidarabad, Lorenzo Leardini and Antonio Nanni. "RC beams shear-strengthened with fabric-reinforced-cementitious-matrix (FRCM) composite" *International Journal of Advanced Structural Engineering* 7 (2015): 341-352.

55. Aljazaeri, Zena R and John J Myers. "Strengthening of Reinforced-Concrete Beams in Shear with a Fabric-Reinforced Cementitious Matrix" *Journal of Composites for Construction* 21 (2017): 04017041.

56. Talayeh, Noshiravani and Brühwiler Eugen. "Behaviour of UHPFRC-RC composite beams subjected to combined bending and shear" (2010).

57. Wang, Guan, Caiqian Yang, Yong Pan and Fawang Zhu. "Shear behaviors of RC beams externally strengthened with engineered cementitious composite layers" *Materials* 12 (2019): 2163.

58. Marcinczak, Dorota and Tomasz Trapko. "Experimental research on RC beams strengthened in shear with PBO-FRCM composites" *Materials Science and Engineering* 365 (2018): 042035.

59. Alabdulhady, Meyyada Y, Lesley H. Sneed and Christian Carloni. "Torsional behavior of RC beams strengthened with PBO-FRCM composite – An experimental study" *Engineering Structures* 136 (2017): 393-405.

60. Kim, Jinsup, Minho Kwon, Hyunsu Seo and Jeonghee Lim "Experimental study of torsional strength of RC beams constructed with HPFRC composite mortar" *Construction and Building Materials* 91 (2015): 9-16.

How to cite this article: Bahij, Sifatullah, Safiullah Omary, Francoise Feugeas and Amanullah Faqiri. "Structural Strengthening/Repair of Reinforced Concrete (RC) Beams by Different Fiber-Reinforced Cementitious Materials - A State-of-the-Art Review." *Civil Environ Eng* 10 (2020): 354 doi: 10.37421/jcce.2020.10.354