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Review

Ultra-High-Performance Fibre-Reinforced Concrete for Rehabilitation and Strengthening of Concrete Structures: A Suitability Assessment

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Abstract: Ultra-high-performance fibre-reinforced concrete (UHPFRC) is a cementitious composite which contains fibres. UHPFRC has emerged as an effective structural retrofitting material due to its superior mechanical properties. In addition, UHPFRC has outstanding durability, ductility and workability; a low permeability; and a high abrasion and fire resistance. These improved characteristics of UHPFRC are obtained by reducing the content of free water in the concrete matrix (leading to less air voids), introducing high strength ductile steel fibres, replacing coarse aggregates with well graded fine aggregates and introducing highly active pozzolanic materials. UHPFRC has excellent bonding with normal strength concrete and it eliminates the issue of debonding which is common in other retrofitting techniques employing fibre-reinforced polymers or externally bonded steel plates. Therefore, considering various aspects, UHPFRC-based structural retrofitting possesses a number of advantages. This paper presents a review of previous studies employing UHPFRC for structural retrofitting applications, highlighting its advantages, limitations and challenges. Aspects of flexural strengthening, combined axial and flexural strengthening, shear strengthening, impact resistance and torsional strengthening are considered for this review. Altogether, the paper aims to enhance the awareness of UHPFRC for structural retrofitting as a step forward towards effective field applications and to outline the potential future directions of research.

Keywords: ultra-high-performance fibre-reinforced concrete; rehabilitation; strengthening; durability

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1. Introduction

Concrete structures are designed for their chosen service lives based on the guidelines of the codes of practice. However, in the recent past, reinforced concrete structures exposed to aggressive environmental conditions have experienced premature deterioration. Moreover, a higher mechanical loading which exceeds the design value enhances early deterioration and can lead to failure [1,2]. The chloride-induced corrosion of steel embedded in concrete is one of the main mechanisms affecting the deterioration of reinforced concrete structures, especially in coastal regions. In addition to the effects of severe mechanical loading and aggressive environmental conditions, there can be occasions where the built structures are altered to cater to the evolving requirements. For example, as a relief measure for traffic congestion on existing road bridges, extra lanes are provided by adjusting the standing lane widths [3]. In these instances, the load on the structure can exceed the intended design load, requiring strengthening of the critical structural components. Furthermore, there can be design errors, mistakes made in the construction phase and changes in the intended use of structures, especially in buildings, which highlights the importance of retrofitting. Considering the aforementioned factors, there is an increasing emphasis on the rehabilitation and strengthening of deficient or damaged reinforced concrete structures.

Strengthening techniques have the potential to restore or enhance the structural performance, satisfying the requirements of the current design codes of practice. Furthermore, rehabilitation and strengthening of structures is a more feasible and sustainable solution in comparison with demolition and reconstruction of new structures considering the resources (e.g., material and time) and economic aspects.

In selecting an appropriate strengthening and rehabilitation technique, both the structural aspects and non-structural requirements need to be considered [4]. Structural aspects refer to the enhancement in the load-carrying capacity by improving the axial, flexural, shear and torsional resistance. Non-structural requirements include minimizing the involved cost, limiting the construction time, overcoming the challenge of space limitations, minimizing the disruption to the occupants during the construction stage and retaining the structure's aesthetics. Moreover, maintaining or enhancing the durability of the structure is of utmost importance. A common challenge associated with strengthening techniques is the localised alteration of the member stiffness, which can specifically change the dynamic properties of the structure. Conventional strengthening techniques are reinforced concrete/mortar jacketing, steel jacketing, external post-tensioning and fibre-reinforced polymer (FRP) jacketing [5–8].

Steel jacketing and reinforced concrete/mortar jacketing were the first proposed strengthening techniques and are capable of providing a significant enhancement in strength and ductility. However, concrete/mortar jacketing can change the cross-sectional size of the members, leading to changes in stiffness and even the seismic demands. Steel jacketing also possesses the same drawbacks of altering the cross-sectional size and affecting the stiffness. Furthermore, due consideration should be given to controlling the corrosion of steel jackets which are exposed to the environment. Given these limitations and drawbacks, FRPs have evolved as an attractive alternative to conventional retrofitting techniques and, more recently, the research focus has been on investigations into the improvements in and applications of FRP strengthening [9–11]. The main challenge in implementing externally bonded FRP jacketing is the debonding, which results in a lowered efficiency. In addition, FRPs exhibit poor properties when exposed to high temperature and a wet environment [12]. Therefore, to address these limitations and shortcomings, UHPFRC has emerged as an effective structural retrofitting material, exhibiting superior mechanical properties, durability, ductility and workability; a low permeability; and a high abrasion and fire resistance. In the recent past, considerable efforts have been put into improving the behaviour of cementitious materials by incorporating fibres into their composition, and these efforts have led to the emergence of UHPFRC. Different types of steel fibres, varying proportions of fibres, the addition of supplementary cementitious materials and different mix proportions have been explored by researchers to enhance the performance of UHPFRC mixes. UHPFRC-based structural retrofitting is a simple and effective technique to enhance the stiffness and load-carrying capacity of reinforced concrete structures, while minimising the change in member sizes and shapes. Therefore, UHPFRC-based structural retrofitting has been applied to a wide array of concrete structures around the world.

This paper provides a state-of-the-art review of the studies employing UHPFRC for structural retrofitting applications. In addition, a brief overview of the factors affecting the mechanical properties of UHPFRC are presented for completeness. The recent advancements in obtaining superior mechanical properties and an enhanced durability of UHPFRC by improving the mix design are detailed. In addition, recent research has focused on the use of different steel fibre types and geometries (aspect ratios) in the UPFRC mix to study its effect on the performance of UHPFRC, which is elaborated here. Furthermore, the sustainable aspects of UHPFRC are studied by incorporating supplementary cementitious materials into the mix, partly replacing the Portland cement. Moreover, the inclusion of industrial by-products and even waste materials into UHPFRC matrices has been recently explored to improve the sustainability of UHPFRC without compromising the performance. The aim of the paper is to enhance the awareness of UHPFRC for structural retrofitting as a step forward towards effective field applications and to outline the future directions of research. Previous studies on UHPFRC exploring the aspects of flexural strengthening, combined axial and flexural strengthening, shear strengthening, impact resistance and torsional strengthening are summarised to provide a complete picture of the attributes of UHPFRC-based structural retrofitting. The novelty of this paper is the comparison of the relative advantages and drawbacks of UHPFRC-based structural retrofitting applications. Retrofitting examples of different structural components such as beams, slabs, columns and walls are presented, which are from previously published experimental results. The main added value of this paper is that the readers can access a summary of all the recent advancements in UHPFRC-based structural retrofitting techniques. Furthermore, the main findings of each experimental and numerical study are presented, highlighting their key attributes. This state-of-the-art review of the key findings related to UHPFRC strengthening will facilitate further investigations by researchers and industry practitioners and the application of the optimum UHPFRC retrofitting procedure for structural capacity enhancement. An introduction to UHPFRC and its mechanical properties are presented in Sections 2 and 3, respectively. Section 4 provides a summary of the research on structural retrofitting applications using UHPFRC, considering the aspects of improving axial, flexural, shear, torsional and impact resistance. Conclusions are drawn from the previous studies, highlighting the research gaps and potential future research directions. The methodology adopted for this paper is illustrated in Figure 1. This figure highlights the main steps of the literature selection, analysis and conclusions.

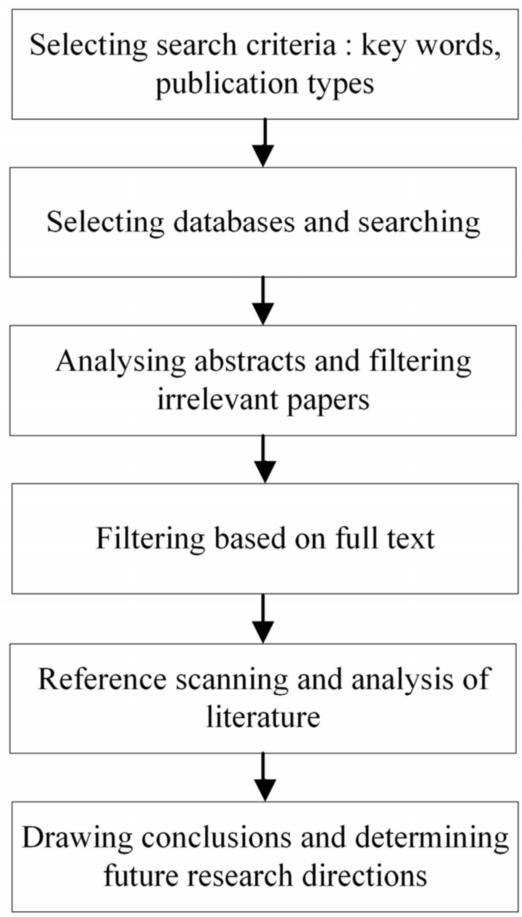


Figure 1. Flow chart of the review methodology.

2. Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC)

UHPFRC is one of the revolutionary discoveries in cement- and concrete-related composites. It can be identified as a cementitious composite material comprised of steel fibres as a reinforcement, replacing conventional reinforcing steel. The initial development of UHPFRC began in the 1970s by investigating high-strength cement pastes with lower water/cement ratios. These pastes were complemented with fibres, superplasticizers and pozzolanic admixtures and paved the way for the introduction of UHPFRC [13]. UHPFRC possesses superior mechanical properties of a compressive strength exceeding 150 MPa, a direct tensile strength higher than 7–8 MPa and a flexural strength more than 30 MPa [14–16]. In addition, UHPFRC exhibits outstanding durability, ductility and workability; a low permeability; and a high abrasion resistance, fire resistance and impact strength [17]. These improved characteristics are obtained by replacing the coarse aggregate with a well-graded fine aggregate to obtain a homogeneous concrete matrix, introducing high-strength steel fibres to improve the ductile behaviour, lowering the water/binder ratio and introducing a super-plasticizer and a highly active pozzolanic material [16,18].

The main differences between UHPFRC and typical reinforced concrete are the presence of the fibres, the size of the aggregate and the amount of binder. The matrix of UHPFRC is much denser in comparison with conventional concrete and the improved mechanical and durability properties are attributed to dense matrix. Achieving the maximum packing density of the granular components is paramount in producing UHPFRC [19]. The introduction of steel fibres enhances the tensile and flexural strength of UHPFRC. Moreover, the steel fibres have the potential to absorb tensile stresses, mitigating the spread and linkage of microcracks [20]. Steel fibres in the UHPFRC mix can have different aspect ratios. It is recommended to use 2–4% steel fibres by mixture volume for a workable and economical UHPFRC mix [21]. The mix proportions of UHPFRC should be selected considering both the economic and sustainable aspects in achieving a denser mix and the optimum composition to gain improved mechanical properties and durability. Different particle packing models have been investigated by researchers to obtain an optimum packing in the matrix and hence to achieve a denser mix [22,23]. A typical mix design of UHPFRC contains Portland cement, silica fume, crushed quartz, fine sand, superplasticizer, steel fibres and water. Most of the commercially available UHPFRC products have been developed in European countries such as France and Germany. In addition, Japan and USA also have succeeded in manufacturing commercial UHPFRC products. Table 1 illustrates the typical mix proportion range by weight in UHPFRCs and the exact mix proportions in some of the commercially available UHPFRC products. The typical chemical compositions (percentage mass) of ordinary Portland cement (OPC) and other supplementary cementitious materials used for UHPFRC mix can be found in Wang et al. [24], and thus are not presented here. Figure 2 illustrates the organization and the contents of this paper. The following section summarises the studies on the mechanical properties of UHPFRC considering the aspects of compressive strength, tensile and flexural strength and impact strength.

Table 1. UHPFRC typical mix design proportion range and mix proportions of commercial UHPFRC products [Adopted from Refs. [25,26]].

Material	Mix Proportion (kg/m^3)		
	Typical Range	Ductal ®	CEMTEC®
Cement	610–1080	746	1050
Silica fume	50–334	242	275
Crushed quartz	0–410	224	-
Sand	490–1390	1066	730
Water	126–261	142	190
Superplasticizer	9–71	9	35
Steel fibres	40–250	161	470

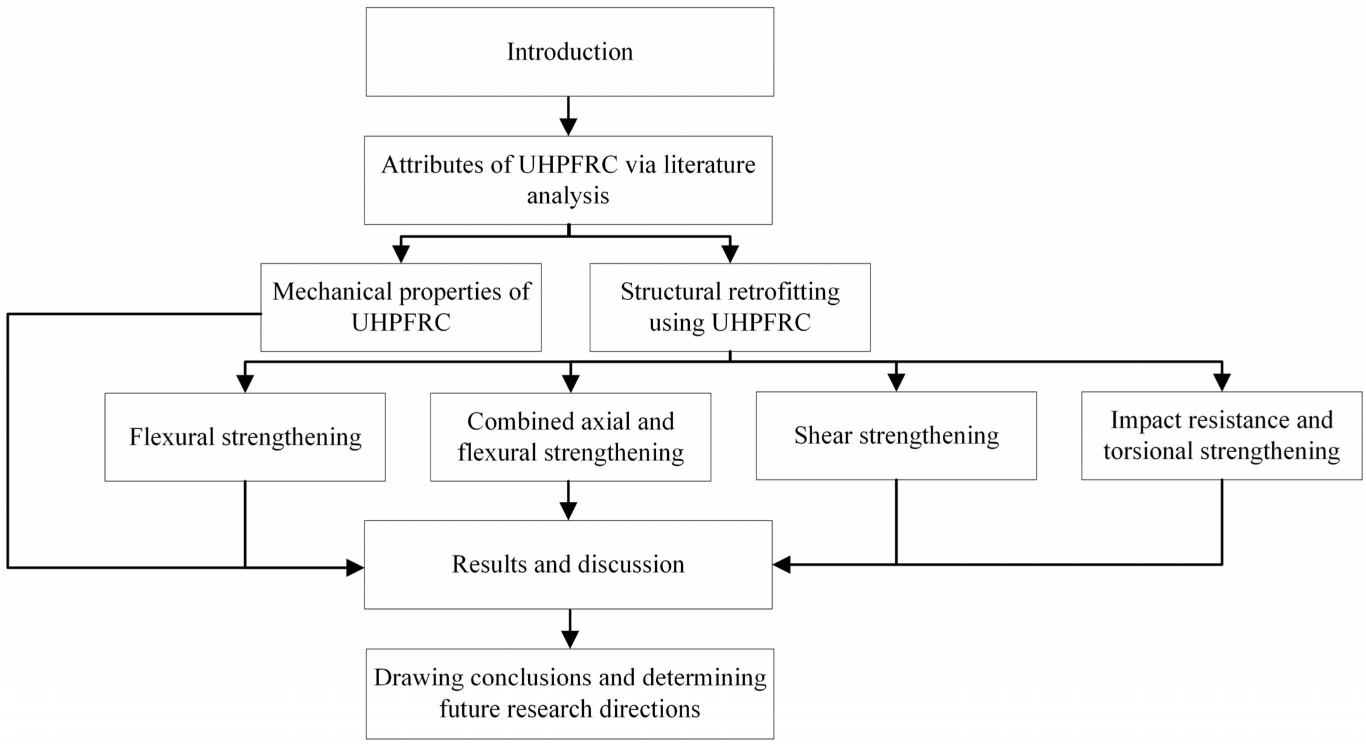


Figure 2. Flow chart of the paper organization and contents.

3. Mechanical Properties of UHPFRC

3.1. Compressive Strength

According to the standards of material testing, compressive strength can be measured either on cubes or cylinders, provided that the conversion factor between the two is validated by design or testing. Cube specimens exhibit higher compressive strength in comparison with cylindrical specimens of UHPFRC due to the confinement effect, and the conversion factors for this difference have been obtained for UHPFRC by researchers [27,28]. Shaikh et al. [29] summarised the variation in compressive strength with the water/cement ratio for more than 70 different mixes of UHPFRC obtained from previous experimental works and thus it is not presented here. The compressive strengths ranged from 150 MPa to 300 MPa and the water/cement ratios were around 0.15–0.25. It was observed that as the water/cement ratio decreases, the compressive strength increases, which is generally true even for concrete with normal strength. Figure 3a illustrates a typical uniaxial compression test set-up used to evaluate the compressive strength. Figure 3b shows the formation of cracks and the failure of UHPFRC cylinders under compression.

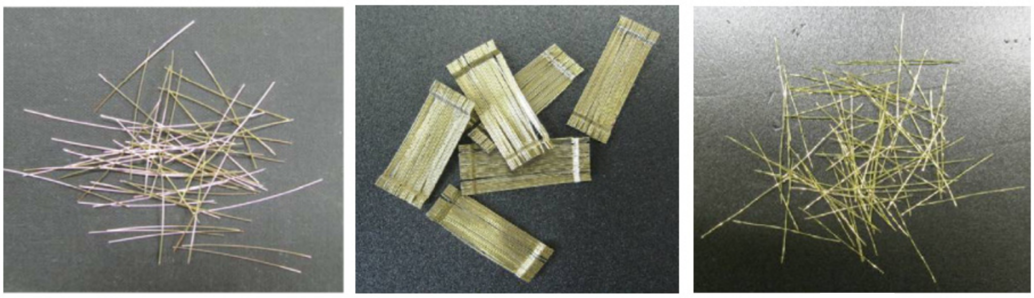
(**a**) (**b**) (**c**)

Figure 3. Evaluation of the compressive strength of UHPFRC. (**a**) Uniaxial compression test set up and (**b**,**c**) formation of cracks and UHPFRC failure ([30]–Elsevier Copyright).

The effects of specimen size on the mechanical properties of UHPFRC have to be considered when working with reduced scale specimens for laboratory testing and these effects must be considered in real structures. Thus, much research has been carried out to investigate the effect of the size of UHPFRC samples [31–33]. The results from these studies indicated that smaller samples possess higher compressive strengths and thus, the size effect of UHPFRC specimens is significant in the context of the compressive strength.

The compressive strength of UHPFRC is partly governed by the effect of pre-treatment. The rate of hydration in the mix can be enhanced by implementing proper heat treatment. The standard curing regime for UHPFRC includes steaming the specimens at 90 °C and 95% relative humidity for 2–6 days [34]. Thermally treated UHPFRC specimens possess a higher 28-day compressive strength compared to those of air-treated specimens [35]. In addition to heat treatment, the application of a confining pressure during the setting of UHPFRC can increase the compactness and thereby positively influence the compressive strength. Nevertheless, when considering the retrofitting applications of the existing structures, the curing regimes for additional strength gain are not pertinent.

The presence of steel fibres enhances the ductility and the tensile strength of UHPFRC. However, previous research has shown the addition of high amounts of steel fibres does not significantly influence the compressive strength enhancement of ultra-high performance concrete (UHPC) [36,37]. El dieb [38] observed that with the increase in the steel fibre volume fraction, the failure mode changed from sudden explosive failure to more characteristic of ductile failure, where the UHPFRC specimen was intact without chipping and spalling. Nevertheless, a significant improvement in compressive strength was not observed with the addition and increase in steel fibres. A slight increase in the compressive strength of UHPC was observed by Abbas et al. [39] with steel fibre addition, while the fibre length had a minimal effect on compressive strength. Introduction of steel fibres to UHPC can result in less entrapped air, increasing the density of the mix and resulting in increased compressive strength. In addition, a slight improvement in the compressive strength of UHPC could be due to the enhanced tolerance of lateral strains with the addition of steel fibres [30,40]. A negative impact of increasing the steel fibre concentration is fibre bundling, which can lead to weak spots, reducing the efficiency of fibres and the homogeneity of the mix. The effect of steel fibre shape and content on the mechanical properties of UHPFRC was investigated by Wu et al. [41]. Three different shapes of steel fibres were used in this study, namely straight, corrugated and hooked ends, and the fibre content was also varied by volume, ranging from 0 to 3%. Similar to the previous findings, the increase in the fibre content resulted in a minor increase in the compressive strength. In contrast, the shape of the steel fibre had a substantial effect on the compressive strength. For UHPFRC specimens with 3% hooked end and corrugated fibres, the increase in 28-day compressive strength was 48% and 59%, respectively, in comparison with specimens with the same amount of straight fibre. Thus, the effect of the steel fibre shape is paramount for compressive strength enhancement. Figure 4 shows different types of steel fibres which can be incorporated into a UHPFRC mix.



(a) (b) (c)

Figure 4. Types of steel fibres: (**a**) smooth macro-fibre, (**b**) hooked macro-fibre and (**c**) twisted macro-fibre ([42]–Elsevier Copyright).

Considering the economic and sustainable aspects, researchers have explored the inclusion of industrial by-products and even waste materials into UHPFRC matrices, without compromising the superior mechanical properties [43–46]. Granulated blast furnace slag, silica fume and fly ash have been used as partial clinker replacements. The results of the aforementioned experimental studies showed that UHPC mixes with lower volume fractions of partial clinker replacements had similar compressive strengths to the reference mix, with only with cement as the binder. Even the use of recycled glass cullets [47], waste ceramics [45] and waste bottom ash [46] did not result in significant reductions in the compressive strength when these materials are used in lower volume fractions in the UHPFRC matrix. One of the main drawbacks of UHPFRC is its high Portland cement content which increases the cost and also results in increased emission of greenhouse gases. Aldahdooh et al. [48] explored the possibility of adjusting the binder content in UHPFRC using the response surface method. It was found that for given water/binder and superplasticizer/cement ratios, the compressive strength did not rely on the binder content. Moreover, the capillary porosity increases with the increase in Portland cement and thus there is no strength enhancement with the increase in binder content.

3.2. Tensile and Flexural Strengths

The tensile and the flexural strengths of UHPFRC are significantly higher compared to conventional reinforced concrete. In UHPFRC, the improved tensile and flexural strengths are attributed to the dense particle packing and the addition of steel fibres. Shaikh et al. [29] presented a detailed summary of the tensile and flexural strength test results found in the literature for UHPFRC and thus they are not reviewed in this paper. Tensile strength was evaluated mostly using "dog-bone" specimens subjected to direct tension [42,49]. Figure 5 illustrates a uniaxial tensile test set-up used to evaluate the direct tensile strength of UHPFRC dog-bone specimens. Figure 5c depicts the formation of cracks and tensile failure. Another approach adopted is the split tensile test arrangement [50]. For flexural strength assessment, three-point and four-point bending arrangements were utilised [48]. These tests were carried out for different specimen sizes and varying fibre contents, types and sizes. The effects of these parameters on the tensile and flexural strength need to be determined. Figure 6a shows a typical four-point bending test set-up used to evaluate the flexural capacity of UHPFRC beams. The initiation of flexural cracks, crack opening and the flexural failure of UHPFRC beams is illustrated in Figure 6b.

(a) (b) (c)

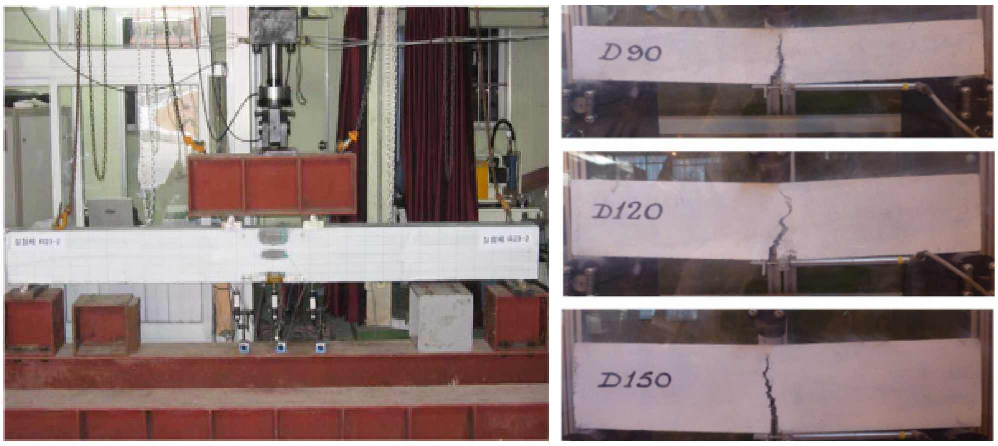
Figure 5. Evaluation of the direct tensile strength of UHPFRC: (**a**) Dog-bone specimens, (**b**) uniaxial tensile test set-up and (**c**) failure of the specimen ([30]–Elsevier Copyright).

Researchers have explored the effect of varying the steel fibre content on the direct tensile and flexural tensile strengths of UHPFRC. It was found that the cracking and peak flexural tensile strength, as well as the strain-hardening behaviour, are improved by the addition of steel fibres compared to a UHPC mix without fibres [51]. Kang et al. [52] conducted notched three-point bending tests to investigate the flexural tensile strength of UHPFRC. A linear increase in the flexural tensile strength was observed when the fibre volume ratio increased from 0 to 5%. However, it was observed that the increase in the fibre content had little effect on the first crack strength and first crack deflection. The failed beam specimens exhibited a single vertical macro-crack along with multiple micro-cracks due to the effect of steel fibres [27]. The role of the fibres is to mitigate the spread of micro-cracks by absorbing the tensile stresses. Eiden et al. [53] observed that the splitting tensile strength increased from 34% to 67% for the steel fibre contents of 1% and 3%, respectively, compared to a UHPC mix without fibres. Additionally, a similar trend was found for the flexural strength. The flexural strengths improved from 15% to 40% with the increase in fibre content from 1% to 3%, respectively, in comparison with a mix without fibres. Wu et al. [41] varied the fibre content and the type of steel fibres in a UHPFRC mix to investigate the effects on the mechanical strength. Introduction of 2% straight, hooked end and corrugated fibres improved the flexural load by 46.3%, 81.1% and 61.4%. Furthermore, the peak deflection improvement was found to be 76.7%, 153.3% and 123.3%, respectively.

Park et al. [42] investigated the effects of blending fibres on the tensile behaviour of UHPFRC. Four types of steel macro-fibres and one type of micro-fibre were considered in this study. It was observed that the addition of micro-fibres into the hybrid system enhanced both the strain hardening and multiple cracking behaviours. The hybrid fibre, with a twisted fibre as the macro-fibre, inserted into UHPFRC produced the best strain hardening behaviour with an ultimate tensile strength of 18.6 MPa, with a corresponding strain of 0.64%. The performance ranking considering the post-cracking strength, strain capacity and multiple cracking behaviour was in the order of long smooth fibres < hooked end fibres < twisted fibres. In addition to the fibre type and content, the fibre orientation also has a considerable influence on the tensile and flexural strengths [54,55].

The size effect needs to be considered when evaluating both the flexural and tensile strengths. Similar to the compressive strength, decreased specimen sizes exhibit increased flexural strengths [33]. Moreover, the ductility is also enhanced in smaller specimens, possibly due to the improved fibre orientation in smaller specimens. Nguyen et al. [56] observed that the average number of cracks, and even the crack spacing, decreased with the decrease in specimen size. Frettlöhr et al. [57] explored the size effect and observed that for axial tension, the elastic limit as well as maximum tensile strength drastically reduced when the specimen depth increased from 25 to 100 mm. Similarly, for bending tests, the increase in prism height resulted in a decreased flexure tensile strength. Thus, the effect of specimen size cannot be neglected when considering the direct tensile and flexural tensile strengths.

In structural retrofitting applications, additional tensile and flexural strength enhancement via high-temperature curing is not applicable since it limits the application for precast UHPFRC products. Therefore, normal temperature curing has to be adopted for in situ construction. Nevertheless, previous research has shown that high temperature steam curing can improve both the tensile and flexural strengths [35]. Yang et al. [47] explored the effects of a curing regime on the mechanical properties of UHPFRC. A comparison of the specimens cured at 20 °C and 90 °C showed that a higher flexural strength was found in specimens cured at 90 °C. A flexural strength reduction of 10% was observed for specimens cured at 20 °C along with about 15% reduction in fracture energy compared with that of specimens cured at 90 °C.



(a) (b)

Figure 6. Evaluation of the flexural strength of UHPFRC. (**a**) Four-point bending test set up and (**b**) formation of cracks and UHPFRC failure in flexure ([33,58]—Elsevier Copyright).

3.3. Impact Strength

Impact strength is another aspect to be considered in structural retrofitting given the possibility of structures being subject to extreme loadings such as earthquakes, gas explosions and vehicle impact. Furthermore, in the recent past, blasts due to terrorist attacks also impart extreme loading on structures. When subjected to impacts, concrete undergoes elevated localised strain rates. Habel and Gauvreau [59] explored the rate-dependent behaviour of UHPFRC by conducting drop weight tests to apply dynamic three-point bending loading on UHPFRC plates. It was observed that both drop weight and quasi-static bending tests had identical failure modes. Ultimately, fracture occurred by fibre pullout in the centre of the specimen and a high moment region exhibited multiple cracking. Yoo et al. [60] examined the flexural behaviour of UHPFRC beams under low velocity impact loading. The experimental programme consisted of testing four large-sized beams using a drop-weight impact test machine. An improvement in the performances under impact loading was observed with the increase in the reinforcement ratio. With the increase in the reinforcement ratio, the maximum and the residual deflections of the beam decreased after the first impact. Thus, higher reinforcement ratios in beams exhibited a better performance for impact loading considering the deflections, crack widths and deflection recovery.

Máca et al. [61] investigated UHPFRC response to deformable and non-deformable projectile impact. A significant enhancement in the impact behaviour in terms of the penetration depth was observed in UHPFRC specimens with added steel fibres in comparison with their plain concrete counterparts. Figure 7 illustrates the effect of a projectile impact on a 50 mm UHPFRC slab. The perforation limit and the borders of the crater on the back side of the slab are shown in Figures 7a and 5b, respectively. Some researchers have conducted experimental testing to investigate the capability of UHPFRC panels to be used in existing structures as protective overlays, since they can avoid or at least mitigate the effect of penetrating projectiles. These overlays contributed substantially to control the back face spalling of the RC walls [62,63]. The experimental results indicated that UHPFRC is a suitable material, with a greater potential to resist extreme load events as its response to impact loading is much better than other cementitious materials such as high-strength concrete [64].

(a) (b)

Figure 7. Effect of a projectile impact on a 50 mm UHPFRC slab: (**a**) perforation limit and (**b**) borders of the crater on back side ([61]–Elsevier Copyright.s)

4. UHPFRC for Structural Retrofitting

The superior performance of UHPFRC in terms of its mechanical properties leads to a range of structural retrofitting applications. In addition, UHPFRC exhibits an extremely low permeability, which prevents the ingress of detrimental substances such as chlorides and water, leading to significant improvements in durability [65–67]. Furthermore, UHPFRC exhibits better rheological properties and flowability in the fresh state, with the use of adequate amounts of water-reducing admixtures allowing for easy in situ casting [68]. Nevertheless, strengthening strips can be prefabricated and utilised for retrofitting to obtain better quality control. In both the in situ and prefabricated retrofitting applications, the bond strength between the UHPFRC and the normal concrete substrate is paramount in determining the composite action. Researchers have experimentally evaluated the bond strength using slant shear tests and split cylinder tensile tests. The results indicated that UHPFRC has excellent interlocking with the surface of normal concrete and the failure modes in the split tensile tests showed that the bond strength is greater than the strength of the normal concrete substrate [16]. Surface preparation methods such as sandblasting result in enhanced bond strength and wet surfaces have exhibited higher bonding than dry surfaces [69,70]. Another important aspect of UHPFRC as a repair material is the rapid strength gains even with ambient air curing, which can lead to speedy construction. All these characteristics illustrate the suitability of UHPFRC for rehabilitation and retrofitting applications.

4.1. Flexural Strengthening

Previous studies have shown that the 28-day flexural strength of typical mixes of UHPFRC ranges from about 25 to 30 MPa [29]. Therefore, UHPFRC jacketing is widely used for flexural strength enhancement. Alaee and Karihaloo [71] explored the strengthening of damaged concrete beams by utilising adhesive-bonded precast UHPFRC strips. Different retrofitting configurations were investigated, such as a single strip bonded on the tension face and multiple strips bonded on the tension face and vertical faces of the test specimens. For the four-point bending tests, significant improvements in the ultimate load were observed. The specimens retrofitted on three sides exhibited an increase in the ultimate load varying from 52 to 102% for different mixes and strip thicknesses of UHPFRC. Habel et al. [72] proposed three different configurations of retrofitting options to improve the flexural performance of existing structures. The first configuration consisted of a thin layer of UHPFRC, whereas the second configuration had a UHPFRC layer for tensile reinforcement to replace an existing strongly deteriorated reinforcement. The third configuration was a reinforced UHPFRC layer on the structural element. It was seen that all the retrofitting configurations led to higher stiffness and increased resistance, while delaying the crack propagation. The results showed that the third configuration was the most effective option. However, attention should be paid in strengthening the tension chord of statically indeterminate systems since there can be reductions in the rotation capacity.

Habel et al. [73] conducted an experimental series by testing 12 full-sized beams strengthened with UHPFRC layers. Six beams contained embedded reinforcement in the UHPFRC layer. The reinforcement percentage of these beams was kept constant at 2% of the UHPFRC cross-section. An increased stiffness, minimised deformation and reduced crack widths and spacings were observed from the strengthening with a UHPFRC layer. This improved performance was attributed to the high tensile strength of the UHPFRC layer and its strain-hardening properties. The addition of reinforcing bars increased the composite members' hardening magnitude three-fold and substantially delayed the formation of localised macro-cracks. A cantilever beam setup was used by Noshiravani and Brühwiler [74] to experimentally investigate the strengthening effect of composite beams. These beams had a depth of 250 mm and consisted of a 50-mm-thick reinforced UHPFRC layer. The test series was carried out by varying the span length, ratio and the type of steel reinforcement. Most of the beams failed in flexure at a force of about 2 to 2.8 times higher than the failure load of the reference reinforced concrete specimens. The response of the composite beams was influenced by the formation of an intermediate crack-induced debonding zone that softened the connection between the RC element and the UHPFRC substrate, increasing the deformation capacity.

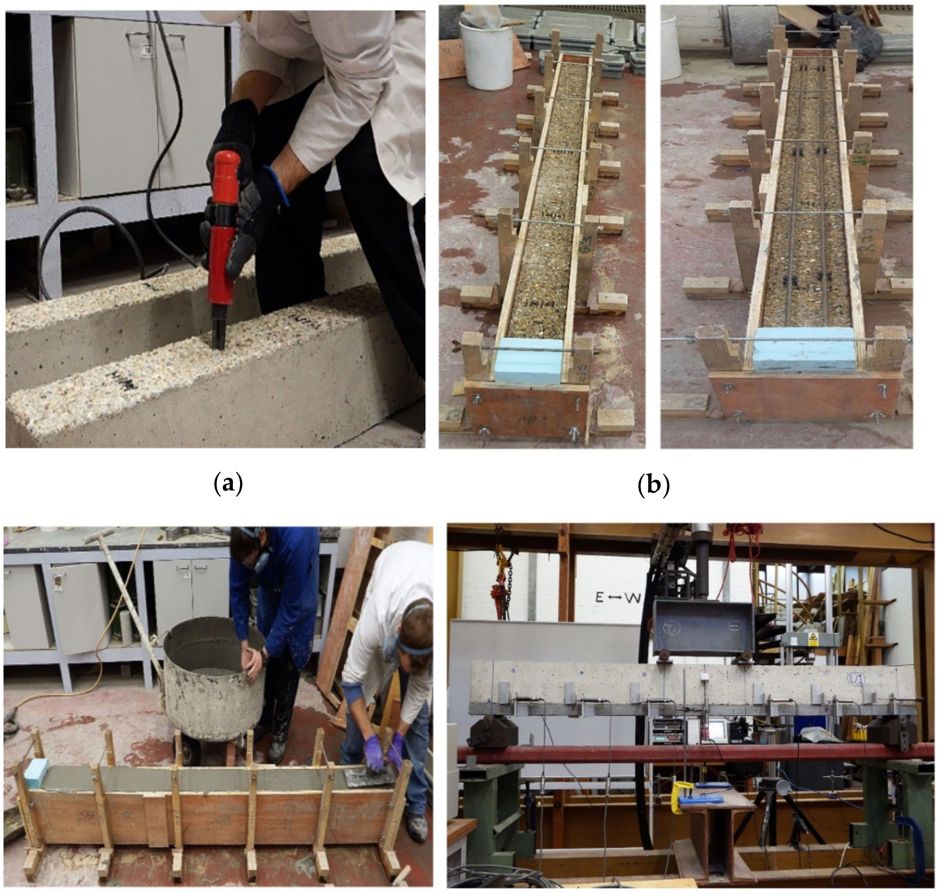
An extensive numerical and experimental investigation was carried out by Lampropoulos et al. [75] to investigate the efficiency of UHPFRC in flexural strengthening of existing beams. The strengthened specimens exhibited a 31% increase in the ultimate moment only in the tension side, whereas the three-side-jacketed specimens exhibited a moment enhancement of 53%. The UHPFRC overlay was complimented with an additional reinforcement layer in the tension side, resulting in a 150% increase in the yield moment along with a 97% increase in the ultimate moment. Thus, it was concluded that three-side jacketing can achieve superior performance and it has the capability to rehabilitate existing structures. Safdar et al. [76] conducted four-point bending tests for six reinforced concrete beams strengthened with UHPFRC layers by varying the thicknesses. In this study, both tension and compression zones were retrofitted. Layer thicknesses of 20, 40 and 60 mm UHPFRC were considered in casting the beams. UHPFRC crushing was observed as the failure mode in specimens with a UHPFRC thickness of 20 mm. In contrast, the other specimens with increased UHPFRC layer thicknesses exhibited failure modes of concrete crushing and rebar fracture. The cracking loads were 30 kN for the reference specimen and 88.5 kN for the tension side-strengthened specimen with a 60 mm UHPFRC layer. For the same specimens, the maximum loads were observed as 118.9 and 156.3 kN, which shows a significant enhancement in flexural capacity. Moreover, the experimental and analytical results indicated an increase in flexural capacity with an increase in UHPFRC thickness.

Considering the economic and sustainable (e.g., embodied energy and greenhouse gas emissions) aspects, the effects of incorporating palm oil fuel ash into UHPFRC without compromising the mechanical properties has been explored by Aldahdooh et al. [77]. In this study, a green UHPFRC mix was developed which contained up to 50% palm oil fuel ash in the composition. This mix resulted in a 28-day compressive strength of 156.7 MPa. In addition, the split tensile and flexural strengths were 20.5 MPa and 42.4 MPa, respectively. This UHPFRC mix has been used to retrofit damaged concrete beams employing precast strips of different configurations. The strength enhancement in 16 and 20 mm strips has been experimentally investigated. A failure load increase in the range of 21–37% was observed in the retrofitted beams compared to that of the reference beam. Furthermore, the strengthened beams significantly enhanced the serviceability criteria.

Tanarslan [78] investigated the behaviour of RC beams strengthened with prefabricated UHPFRC laminates. Six under-reinforced beams strengthened with 50-mm-thick UHPFRC laminates along with a control beam were subjected to four-point bending tests. Both epoxy bonding and anchorage bonding procedures were employed along with and without reinforcement in the laminate substrate. The main disadvantage identified in this strengthening process was the higher quality control and workmanship required in fabricating and applying the laminates. However, the results of the UHPFRC-strengthened specimens indicated a minimum percentage increase in the load carrying capacity of 32%, whereas the maximum increase was about 208%. This study was extended by Tanarslan et al. [79] to understand the effects of the bonding technique of the laminates on the strength performance. Mechanical anchoring and gluing with epoxy were employed to attach UHPFRC laminates to retrofit RC beams with a lower flexural strength. Both glued specimens and anchored specimens resulted in similar ultimate loads for the reinforced UHPFRC laminates. Moreover, the specimen with a glued UHPFRC laminate failed abruptly without showing any ductility. The failure mode was changed from flexure to brittle concrete cover separation. The minimum increase in the load-carrying capacity was found to be 7%, whereas the maximum increase was 118%.

A comparison of the performance of concrete beams strengthened by bonding prefabricated UHPFRC strips was carried out by Al-Osta et al. [80]. Here, UHPFRC strips were casted in situ around the beams. Three different configurations of retrofitting were adopted, such as single, double and triple longitudinal side strengthening. In single side strengthening, the bottom side was retrofitted. The slant shear stress test results showed that casting UHPFRC strips in situ leads to a higher bond strength compared to prefabricated UHPFRC strips bonded with epoxy. In situ casting was carried out after roughening the surface by sandblasting and this further enhanced the bond strength. Both techniques proved to be effective in enhancing the flexural strength. However, sandblasting and in situ casting of UHPFRC showed an overall better performance. Beams strengthened on three sides exhibited the highest moment capacity enhancement in comparison with the other two configurations. Dagenais and Massicotte [81] investigated the cyclic behaviour of lap splices strengthened with UHPFRC. In this study, the splice region was strengthened by removing normal concrete around the lapped bars and replacing it with UHPFRC. For the experimental work, a single fibre type was used with three fibre contents. In addition, two bar diameters were employed with two different arrangements. Testing was carried out for six large-scale RC beams. These beams had deficient lap-splice details and the cyclic behaviour was explored by strengthening with UHPFRC. The region along the splice length was subjected to constant moment when performing the bending tests. Longitudinal splits were observed close to the splice bars and this was the dominant failure mode of the tested specimens. The results illustrated that UHPFRC with an appropriate fibre content can ensure the continuity of lapped bars. This can improve the structural integrity of members subjected to cyclic loading.

A numerical simulation of the structural response of RC cantilever beams retrofitted with UHPFRC was conducted by Sadouki et al. [82]. The complex cracking phenomena of the composite beams were simulated by finite element modelling incorporating actual nonlinear material models. Load–deflection curves of previous experiments were used in validating the numerical models. Modelling was carried out in DIANA software and based on the smeared crack approach. A good agreement between the experimental and numerical load–deflection responses were obtained for the retrofitted cantilever beams. Specifically, the peak resistance was accurately predicted. A validated numerical model can be subsequently used to investigate the behaviour of UHPFRC retrofitted structures. Paschalis et al. [83] explored the performance of UHPFRC for strengthening RC beams. This study consisted of both experimental and numerical investigations. Figure 8 illustrates the flexural strengthening of RC beams using UHPFRC overlays. The surface preparation is illustrated in Figure 8a,b, showing the prepared beams ready for the casting of the UHPFRC layers. Casting of the UHPFRC layer and the four-point bending set-up are shown in Figure 8c,d, respectively. In addition to the four-point bending tests, push-off tests were also carried out to study the interface between the UHPFRC and the concrete substrate. Additionally, smaller values of slip at the interface were recorded, indicating a better bond between the two materials. Compared to the control specimens, retrofitted beams with a UHPFRC layer and steel bars illustrated an average maximum load increase of 87%. The amount of reinforcement added to the UHPFRC overlay and the thickness of the layer were the key parameters determining the strength enhancement.



(**a**) (**b**)

(**c**) (**d**)

Figure 8. Flexural strengthening using UHPFRC overlays. (**a**) Surface preparation of the beams, (**b**) beams ready for casting of the layer (unreinforced and reinforced), (**c**) casting the UHPFRC layer and (**d**) four-point bending test set-up ([83]—Elsevier Copyright)

Mismatch between the tensile strength and the stiffness are the main limitations in rehabilitation using externally bonded steel plates and fibre-reinforced polymer laminates. To address this issue, Murthy et al. [84] examined the performance of RC beams retrofitted with thin UHPFRC strips. UHPFRC strips (10 mm) with a 2% volume fraction of brass-coated steel fibres were utilised in the strengthening of RC beams with different damage levels. Most of the retrofitted beams were failing by yielding the steel reinforcement and subsequent concrete crushing. This is similar to the predominant failure mode in RC beams. There was an enhancement in the load-carrying capacity of the retrofitted RC beams in comparison with the reference RC beams. This study was extended by Murthy et al. [85] to explore the fatigue behaviour of the strengthened RC beams with thin UHPFRC strips. Figure 9 shows the prefabrication of UHPFRC strips, the surface preparation of the beams and the epoxy adhesive bonding of UHPFRC strips. Pre-loaded and retrofitted beams were tested under fatigue loading with a stress ratio of 0.1 and a frequency of 2 Hz. The maximum number of cycles to failure of all pre-loaded and retrofitted RC beams was found to be substantially higher than that of the control beams.

(a) (b)

Figure 9. Strengthening of RC beams using UHPFRC strips. (**a**) Prefabrication of UHPFRC strips and (**b**) surface preparation and epoxy adhesive bonding of UHPFRC strips ([84]—Elsevier Copyright).

Most of the previous studies on flexural strengthening using UHPFRC have been focussed on concrete beams. Nevertheless, this approach can be extended to slabs. Yin et al. [86] carried out an experimental programme testing nine rectangular composite RC slab (1600 mm × 300 mm) specimens retrofitted with UHPFRC. The behaviour of strengthened slab panels was investigated. The height of the panels ranged from 100 to 150 mm and different configurations of UHPFRC retrofitting were implemented. The results of three-point bending tests showed that the strengthening results in reduced diagonal cracking while developing more flexural cracks. An improved ductile performance with deflection hardening was observed in the post-cracking stage, exhibiting good energy absorption. For the overlay specimens, the ultimate load was in the range of 73 to 95 kN, compared to 61 kN for the control specimen. Considering all the aspects, it was concluded that UHPFRC strengthening has a great potential in rehabilitation and retrofitting of structurally deficient RC slabs. UHPFRC technology is widely used in bridge deck strengthening and field applications have been reported in previous works [87–89]. The analytical design rules which can be used in calculating the increase in structural resistance are presented in these studies. Lower intervention costs, a reduced complexity of execution and long-term cost effectivity have been identified as the main advantages of UHPFRC strengthening in comparison with the traditional strengthening techniques. A summary of the studies on flexural strengthening of RC members using UHPFRC is presented in Table 2.

Table 2. Summary of the studies on flexural strengthening using UHPFRC.

Study	Type of Structural Member, Strengthening and Testing Method	Results/Remarks
[71]	Retrofitting damaged RC beams by adhesively bonding precast UHPFRC strips; Testing using four-point bending setup.	Increase in the ultimate load with the increase in UHPFRC strip thickness.
[72]	Strengthening damaged RC beams by reinforced and unreinforced UHPFRC layers; Investigation using an analytical cross-sectional model.	Retrofitting configurations lead to higher stiffness and increased resistance, while delaying crack propagation.
[73]	Four-point bending test of full-size RC beams strengthened with UHPFRC layers.	The addition of reinforcing bars in the UHPFRC layer significantly increased the composite members' flexural capacity and delayed the formation of localised macro-cracks.
[74]	Testing of UHPFRC-strengthened beams using a cantilever beam setup by varying span length, ratio and type of reinforcement.	Strengthened beams failed in flexure at a force about 2 to 2.8 times higher than the failure load of reference RC specimens.
[75]	Four-point bending test of existing RC beams strengthened with UHPFRC layers (tension side, compression side and three-side-jacketing configurations).	Three-side-jacketed beams complimented with additional reinforcement exhibited the highest flexural capacity enhancement.
[76]	Four-point bending test for RC beams repaired in the tension and compression zone with UHPFRC layers of varying thicknesses.	Significant increase in the cracking and ultimate load for strengthened beams with higher UHPFRC layer thickness. Concrete crushing and rebar fracture failure modes were observed.
[77]	Retrofitting damaged RC beams with prefabricated strips of UHPFRC containing up to 50% palm oil fuel ash. Testing using four-point bending setup.	Increase in the average failure load within the range of 21 to 37% compared to refence RC beams.
[78]	Four-point bending test of RC beams strengthened with prefabricated UHPFRC laminates. Epoxy bonding and anchorage bonding were implemented.	A maximum load-carrying capacity increase of 208% was observed for reinforced UHPFRC-strengthened beams. Higher quality control and workmanship required.
[79]	Four-point bending test of RC beams strengthened with UHPFRC laminates. Compared epoxy bonding and mechanical anchorage.	Both anchoring mechanisms showed similar ultimate loads. The glued specimen had lower ultimate deflection.
[80]	Comparison of the performance of beams strengthened by bonding UHPFRC strips and casting UHPFRC layers in situ; Testing using four-point bending setup.	No significant difference in the results for flexural testing using both techniques. However, the sandblasting/UHPFRC cast in situ technique showed an overall better performance.
[81]	Investigated the cyclic behaviour of lap splices of RC beams strengthened with UHPFRC with varying fibre contents and reinforcement arrangements; Tested with reverse cyclic loading.	UHPFRC with appropriate fibre content can provide the continuity of lapped bars, ensuring better ductile performance under cyclic loading.
[82]	Numerical simulation of the structural response of RC cantilever beams retrofitted with UHPFRC.	Strengthened beams using UHPFRC and reinforced UHPFRC increased the flexural capacity of beams by 40% and 53%, respectively, compared to the reference beam.
[83]	Experimental and numerical investigation of the performance of UHPFRC-strengthened RC beams; Four-point bending and push-off testing.	A better bond between the UHPFRC layer and concrete substrate was observed. Average maximum load increase of 87% for the retrofitted beams compared to control beams.
[84]	Four-point bending test of damaged RC beams restored with thin UHPFRC strips. Finite element models were developed to predict the flexural response of retrofitted beams.	No debonding/delamination of UHPFRC strips was observed. Preloaded and retrofitted RC beams had a slightly higher load carrying capacity than the undamaged control beams.
[85]	Investigated the fatigue behaviour of damaged RC beams restored with thin UHPFRC strips by conducting fatigue testing.	The maximum number of cycles to failure of all pre-loaded and retrofitted RC beams was found to be substantially higher than that of the control beams.
[86]	Experimental investigation of the behaviour of composite RC slabs strengthened with UHPFRC; Tested using three-point bending setup.	Strengthened slab panels showed improved ultimate load. Post cracking range exhibited excellent energy absorption with excessive deflection hardening and ductility.

4.2. Combined Axial and Flexural Strengthening

RC columns in buildings and bridge piers located in earthquake-prone regions require seismic retrofitting and rehabilitation. The primary reason for this is the displacement of columns to dissipate the imposed seismic energy; thus, slight or severe damage can occur in columns depending on the severity of the earthquake. Moreover, ageing structures are subjected to deterioration over their service life. Given these factors, researchers have explored the capability of UHPFRC jacketing to enhance the axial and flexural capacities of structural components such as bridge piers and columns. Different strengthening mechanisms can be identified as a result of UHPFRC jacketing such as cross-section enlargement effect, the passive confinement effect and the gap opening effect [90].

Deficient lap splices in bridge piers are crucial considering the structural integrity and these elements can be strengthened with UHPFRC cover. The behaviour of UHPFRC retrofitted bridge pier specimens were investigated by Massicotte et al. [91]. In the proposed technique, conventional demolition methods were used to remove the concrete around bars in lap splice regions. Then, the removed concrete is replaced by UHPFRC which eliminated splitting cracks and transferred the lapped bar force through the surrounding UHPFRC. Testing of bridge pier specimens was carried out by providing a constant axial load and increasing the lateral displacement cycles incrementally. Ductile behaviour was exhibited by the specimens and the observed failure mode was the tensile rupture of the dowel bars in the footing. The original column shape and dimensions are preserved in the proposed technique contrary to column jacketing. Dagenais et al. [92] extended this study for columns with a cross-sectional aspect ratio exceeding two. The same strengthening approach was implemented and five retrofitted specimens, along with the control specimen, were tested by applying unidirectional reverse cycles. The failure of all retrofitted specimens was ductile and progressive, avoiding the splitting failure of the lapped splice. Furthermore, buckling was not observed for bar diameters of 25 to 45 mm. In addition, the concrete damage failure modes of crushing and spalling were avoided by the UHPFRC cover integrity. It was concluded that this technique can be applied for any location along columns with deficient reinforcement details.

Lavorato et al. [93] explored the seismic behaviour of bridge piers with insufficient seismic durability which were retrofitted with UHPFRC. The proposed UHPFRC interventions specifically focussed on the regions in the plastic hinge zone to improve the ductility and guarantee plastic seismic energy dissipation. Cyclic tests were carried out on 1:6 scaled pier specimens which were repaired and retrofitted. Furthermore, numerical analyses were performed to better understand the behaviour of the strengthened piers. The repaired specimens did not exhibit shear rupture. A higher moment capacity was obtained for the retrofitted pier specimens due to the increase in the inner lever arm. This was mainly due to the reduced height of the compression zone resulting from the high compressive strength of UHPFRC. UHPFRC has wide applications in bridge engineering and Zhou et al. [94] have reviewed the previous research on these applications. In terms of retrofitting, the bridge deck and pier applications were found to be prevalent. The primary deficiencies of UHPFRC were highlighted, such as corrosion of the surface of the steel fibre and the possibility of cracking. UHPFRC consists of a lower water/binder ratio and thus, to improve the workability, a large amount of admixture is used in the mix. As hydration shrinkage progresses, if handled improperly, cracking is inevitable.

Pseudo-static cyclic loading tests were performed by Tong et al. [90] in one "as-built" and two UHPFRC-strengthened full-scale bridge pier specimens. Figure 10 shows the surface preparation of the pier, the casting of the UHPFRC jacket and the curing of the jacket-retrofitted piers. The damage evolution, ductility and strength and stiffness behaviours were explored. Furthermore, the energy dissipation mechanisms were studied. Jacketing heights of 400 and 850 mm were used for a 2.3 m heigh specimen. Both jackets were effective in enhancing the piers' lateral load carrying capacity. Moreover, UHPFRC jackets improved the RC piers' self-centring capability while minimising the residual lateral drift. A peak strength enhancement of 16.2% was obtained for piers retrofitted with a

400 mm jacket height, whereas the peak strength increase was 37.5% for the strengthened specimen with an 850 mm jacket height. Nevertheless, the results indicated that increasing the jacket height negatively affects the ductility increase. Tong et al. [95] extended this study to investigate the effect of two different configurations of UHPFRC jackets. One pier was retrofitted with a single wide strip UHPFRC jacket, and another two specimens were retrofitted with a multi-narrow strip UHPFRC jacket. Piers with a single wide strip UHPFRC jacket exhibited a higher lateral strength; however, they were prone to plastic hinge relocation. In contrast, using multi-narrow strip UHPFRC jackets resulted in a better ductility enhancement. Both techniques were capable of mitigating the residual drift and concrete damage, leading to improved seismic resilience of piers.

(a) (b) (c) (d)

Figure 10. Strengthening RC piers using UHPFRC jacketing. (**a**) Surface preparation of the column, (**b**) casting the UHPFRC jacket, (**c**) casted UHPFRC jacket and (**d**) curing the UHPFRC jacketed columns ([90]—Elsevier Copyright).

Developments in numerical and analytical models are also essential to better understand the performance of UHPFRC-strengthened structural components. Sakr et al. [96] developed finite element and analytical models to investigate the behaviour of UHPFRC retrofitted RC columns under axial or eccentric loading. The main objective of this study was to produce a load-moment interaction envelope for retrofitted RC columns. Finite element models were validated and the validated model was subsequently used for a parametric study. The effects of interfacial shear, jacket thickness and the number of dowels were investigated. The results illustrated that a monolithic behaviour of strengthened columns can be obtained by using an adequate number of dowels, reducing the jacket thickness and by improving the core surface texture. Another numerical study was carried out by Li et al. [97] using 3D finite element models to explore the cyclic response of UHPFRC tube-confined piers. The experimental results were used to validate the finite element models. The validated numerical model was utilised to conduct a sensitivity study considering different material and factors related to geometry. The performance of the UHPFRC tube-confined piers was evaluated by considering five variables such as residual drift, equivalent viscous damping, load-carrying capacity, initial stiffness and hysteretic energy dissipation. The results of the conducted study led to the development of predictive equations to estimate the response of UHPFRC tube-confined columns via regression analysis.

Elsayed et al. [98] conducted an extensive experimental programme to investigate the performance of UHPFRC-strengthened columns under eccentric loading. Twelve rectangular columns were tested by varying the thickness of UHPFRC, the load eccentricity ratio and the volume ratio of the fibres. Additional different strengthening schemes were considered for testing. The results indicated that the gain in moment capacity, axial load capacity and stiffness is inversely proportional to the eccentricity ratio and proportional to the UHPFRC jacket thickness. Full casting with UHPFRC jacket schemes were found to be more effective than bonding laminate schemes. The highest achieved axial load capacity in a strengthened column was 1305 kN, compared to 575 kN in the control beam. The highest primary moment capacities in a strengthened column and the control beam were 56.4 and 21.6 kNm, respectively. In addition to the experimental work, moment interaction diagrams also were analytically developed to predict column strength. Eshaghi-Milasi et al. [99] examined the behaviour of circular RC columns retrofitted with UHPFRC jackets under concentric and eccentric loading. The effect of interface treatment by the longitudinal grooving method and UHPFRC jackets containing synthetic macro-fibres (barchip) were explored. Testing was carried out for small-scale columns of 120 mm diameter and 500 mm height. The load eccentricities were varied from 0 mm to 30 mm to 60 mm. A higher moduli of rupture was obtained for specimens retrofitted with steel fibres when compared to that of barchip fibres. The test results of the strengthened columns revealed a ductility reduction with the increase in load eccentricity. It was concluded that UHPFRC jackets attributed to the enhancement in the load-carrying capacity of RC columns under eccentric loading. Furthermore, the ductility and energy dissipation were enhanced upon retrofitting with UHPFRC.

A summary of the studies on combined axial and flexural strengthening of RC members using UHPFRC jacketing is illustrated in Table 3. Considering the previously conducted experiments and the numerical simulation and analytical model developments, it can be concluded that UHPFRC jacketing can significantly enhance the axial load carrying capacity, moment capacity, ductility, energy dissipation and crack control in RC columns. In addition, the blast and impact resistance are also improved by UHPFRC jacketing. Nevertheless, specific attention should be paid in determining the jacket height and thickness, the type of fibres used and the jacketing configuration, since these parameters have a substantial influence on the dynamic performance of UHPFRC-strengthened columns. Moreover, the interfacial shear is crucial for the bond between the UHPFRC overlay and the underlying RC substrate. Vertical or horizontal grooving and other surface preparation techniques (e.g., sandblasting) can be adopted to ensure a sufficient interfacial bond strength.

4.3. Shear Strengthening

4.3.1. Beams

In typical limit state design concepts, the flexure ductile failure mode is expected for structural components. However, brittle shear failures can be possible for beams with smaller span-to-depth ratios or structural components with a deficient shear resistance. Shear strengthening can be carried out to avoid these brittle shear failures which violate the limit state design concept. Noshiravani and Brühwiler [100] presented the results of an experimental programme for strengthening RC beams with UHPFRC. A cantilever beam test set-up was used to test beams with a span of 1600 mm and a lever-arm length of 800 mm. UHPFRC layers were cast on the tension side of the member, complimented with varying passive reinforcement amounts. Flexure shear failure was observed in the control specimen, which had a peak moment of 34.6 kNm, whereas the strengthened specimens exhibited a maximum peak moment of 72.7 kNm. Initially, critical flexure shear cracks were observed, which reduced the RC element contribution to the member shear resistance with increasing crack opening. The UHPFRC layer significantly enhanced the shear strength of the specimens without compromising the deformation capacity.

Table 3. Summary of the studies on combined axial and flexural strengthening using UHPFRC.

Study	Type of Structural Member, Strengthening and Testing Method	Results/Remarks
[91]	Explored the behaviour of UHPFRC-strengthened bridge pier specimens (originally with deficient lap splices) subjected to constant axial load and increasing lateral displacement.	Splitting cracks were eliminated, exhibiting ductile behaviour, and progressive failure was caused by the dowel bar's tensile rupture in the footing.
[92]	Conducted unidirectional reverse cyclic tests for RC column specimens with deficient lap splices strengthened with a UHPFRC cover.	The concrete damage failure modes of crushing and spalling were avoided by the UHPFRC cover integrity. The failure of all retrofitted specimens was ductile and progressive.
[93]	Investigated the seismic behaviour of bridge piers with insufficient seismic durability which were retrofitted with UHPFRC. Cyclic tests were carried out on repaired and retrofitted 1:6 scale pier specimens.	Strengthened piers showed an increased moment capacity, eliminating failure by shear rupture.
[94]	Reviewed the applications of UHPFRC retrofitting in bridge engineering.	UHPFRC retrofitting improved the issues related to deformation and cracking of bridge pavements while enhancing the connection integrity of joints. The primary limitations of UHPFRC retrofitting were identified as corrosion of the surface steel fibre and the possibility of cracking.
[90]	Conducted pseudo-static cyclic loading tests on as-built and UHPFRC jacket retrofitted full scale bridge pier specimens.	Jackets enhanced the RC piers' lateral load carrying capacity, improved the piers' self-centring capability and mitigated the residual lateral drift.
[95]	Compared the performance of two different UHPFRC jacket configurations (single wide strip jacket and multi-narrow strip jackets) for seismic retrofitting of bridge piers by conducting cyclic tests.	Both techniques mitigated the residual drift and concrete damage, leading to the improved seismic resilience of piers. Piers with a single wide strip UHPFRC jacket exhibited higher lateral strength; however, they were prone to plastic hinge relocation.
[96]	Developed finite element and analytical models to investigate the behaviour of UHPFRC retrofitted RC columns under axial or eccentric loading.	The results illustrated that a monolithic behaviour of the strengthened columns can be obtained by using an adequate number of dowels, reducing the jacket thickness and improving the core surface texture.
[97]	Investigated the cyclic response of UHPFRC tube-confined piers using 3D finite element models.	Predictive equations were proposed to foresee the response of UHPFRC tube-confined columns through regression analysis.
[98]	Conducted an extensive experimental programme to investigate the performance of UHPFRC-strengthened columns under eccentric loading by varying the load eccentricity ratio, volume ratio of fibres, thickness of UHPFRC and strengthening scheme.	The results indicated that the gain in moment capacity, axial load capacity and stiffness is inversely proportional to the eccentricity ratio and proportional to the UHPFRC jacket thickness.
[99]	Examined the behaviour of circular RC columns retrofitted with UHPFRC jackets under concentric and eccentric loading.	The enhancement in the load-carrying capacity of RC columns under eccentric loading was attributed to UHPFRC jackets. Furthermore, the ductility and energy dissipation were enhanced.

Meda et al. [101] conducted four-point bending tests on UHPFRC-strengthened short RC beams lacking shear stirrups. The jacket thickness and configuration were varied in the strengthened specimens. The shear failure mode was observed for the control beam with an ultimate load of 450 kN along with a failure moment of 180 kNm. All the strengthened beams were capable of avoiding brittle shear failure and exhibited flexural failure. The highest failure load and moment for the strengthened beams were 773 kN and 309 kNm, respectively. The UHPFRC jackets allowed the maximum theoretical bending capacity to be reached, shifting the peak load from shear to flexure. This illustrated the effectiveness of UHPFRC jacketing for strengthening shear-deficient beams. Instead of pouring fresh UHPFRC around the RC members for jacketing, prefabricated sheets can be bonded to the RC members at the required locations for strengthening. Aghani and Afshin [102] investigated the shear retrofitting of RC beams by prefabricated UHPFRC sheets. Three-point bending tests were carried out on shear deficient RC beams, which were reduced scale specimens with dimensions of 10 × 20 × 150 mm. Epoxy adhesive was used to bond the prefabricated UHPFRC sheets to the RC beams and debonding was not observed during the tests. The sudden failure mechanism of the control beams was changed to a pre-warning failure mechanism with the retrofitting. Moreover, the prefabricated UHPFRC sheets were able to increase the bearing capacity of RC beams by ~25%.

A similar experimental study was conducted by Garg et al. [103] to explore the retrofitting of shear-deficient RC beams using UHPFRC. In contrast to previous tests, this study employed UHPFRC retrofitted beams which were initially stressed beams to 60% of ultimate failure load. Both under-reinforced and over-reinforced beams were retrofitted with different UHPFRC jackets and tested to investigate their behaviour in terms of ultimate failure load, stiffness and energy absorption. Load carrying capacity enhancements of 24.4% and 28.4% were observed for over-reinforced and under-reinforced U-jacketed beams, respectively. A ductility enhancement of up to 91% in comparison with the reference beam was obtained by incorporating hooked fibres into the matrix. Furthermore, fibres were effective in delaying the crack propagation. The bond strength of the UHPFRC layer with the RC surface, and the concrete confinement provided by UHPFRC were identified as key features accounting for the performance improvement.

4.3.2. Slabs

Shear strengthening of RC slabs is important, especially considering the punching shear capacity. Zohrevand et al. [104] strengthened the punching shear area of flat slab specimens with UHPFRC and testing was carried out for ten half-scale specimens. The steel reinforcement ratio and the depth of UHPFRC were varied for test specimens and a concentric load was applied in the experimental programme. A 70% increase in the punching shear capacity was obtained for slab specimens strengthened with a full-depth UHPFRC layer to an area from the column face up until a distance equal to the slab thickness. The optimal configuration was found to be a partial application of UHPFRC. Nevertheless, a half-depth application of UHPFRC did not exhibit substantial improvements in the punching shear resistance of flat slab specimens. A flat slab made fully from UHPFRC showed a punching shear capacity more than three times higher than its RC counterpart. However, slab specimens cannot be fully constructed from UHPFRC considering the economic aspects.

RC slabs with deficient shear resistance can be strengthened by the addition of UHPFRC layers on the top and this was investigated in [105]. Layers of UHPFRC (25–50 mm thick) were added to RC slabs, and the effect of these layers on the shear transfer mechanism of the resulting composite section was explored. Furthermore, analytical model predictions of the shear and punching shear resistances of the composite sections were presented. It was found that a UHPFRC layer carries shear by an out-of-plane bending mechanism along with near interface cracking, similar to the dowel action of rebars. In slender composite sections under shear, near interface cracking develops fully and plastic hinges are formed. A parametric study on the shear resistance models showed that the shear span-to-depth ratio is critical for the shear capacity. Yin et al. [86] experimentally investigated the behaviour of RC slabs strengthened with UHPFRC concrete. Nine rectangular specimens were tested with various UHPFRC strengthening configurations. One series of specimens was a rehabilitation series in which UHPFRC was used as a patch material for repairing deteriorated concrete and the other was an overlay series where UHPFRC was used to strengthen the soffit of RC members. The maximum ultimate loads were 113 and 95 kN for the rehabilitation and overlay series, respectively, compared to 61 kN for the control specimen. Furthermore, with the increase in the UHPFRC layer thickness, the failure mode changed from brittle diagonal shear to ductile flexure. In the overlay series, the overall stiffness of the slab was improved by the overlay, while simultaneously delaying the development of shear cracks.

Analytical model developments for shear capacity prediction are equally important as experimental studies. Wu et al. [106] presented a theoretical model for predicting the punching shear strength of axisymmetric RC slabs strengthened with UHPFRC layers. The numerical analyses results were used to validate the proposed model, along with the existing experimental results. The validated model was used to carry out parametric studies to investigate the effects of UHPFRC strengthening on the punching shear capacity enhancement of RC slabs. It was found that an increase in the UHPFRC overlay thickness to RC slab thickness ratio affects the enhancement in punching shear strength. It was observed that the yield strength and rebar ratio of the UHPFRC layer did not have a significant effect on the punching shear capacity enhancement or on the ductility of the strengthened slab. It was concluded that the punching shear strength of a composite UHPFRC-RC flat slab is a function of thickness and the strength of UHPFRC overlay.

4.3.3. Columns

Shear retrofitting of RC columns is carried out mainly using jacketing, typically for the purpose of seismic strengthening. Jacketing is applicable to restore critically damaged RC columns or to strengthen moderately damaged/undamaged columns locally or globally. Koo and Hong [107] tested four half-scale UHPFRC-strengthened RC columns by varying the stirrups and jacket thickness. Surface preparation was conducted by sandblasting to obtain a proper bond between the UHPFRC overlay and the RC substrate. For the testing, initially, a constant axial load was applied and then a displacement-controlled horizontal cyclic load was applied. When the UHPFRC layer was complemented with stirrups, the initial cracks did not extend to large diagonal tension cracks and the column failed by flexural yielding. The shear strength of the strengthened columns increased with the increase in the UHPFRC jacket thickness. A 70% shear strength enhancement was observed for columns retrofitted with jackets with a thickness of 10% of the column thickness and a 125% enhancement was found for a jacket thickness of 16.7% of the column thickness. A further strength gain was achieved with the addition of transverse reinforcement in the UHPFRC layer.

Hong et al. [108] conducted an experimental programme to explore the behaviour of retrofitted columns by UHPFRC jacketing with/without textile reinforcement. Both carbon and glass textile reinforcement were used, varying the percentage volume ratio. Slant shear tests were carried out to evaluate the shear strength between the UHPFRC layer and the RC column. Furthermore, the effect on the shear load path was explored due to the discontinuity of tensile forces in the UHPFRC jackets at the floor level of the columns. Seismic retrofitting by UHPFRC jacketing with textile reinforcement increased the shear strength along with the axial and flexural strengths. It was found that the deformation capacity of the strengthened columns at the peak load relies on the ductile behaviour of textile reinforcement in the jackets. Textile reinforcement can influence the failure mode of retrofitted columns. A shear failure can be converted to a flexural failure by the ductile behaviour of textile reinforcement. It was concluded that both the strength and ductility enhancements via UHPFRC jacketing can be effectively applied to shear critical members for seismic upgrading.

4.3.4. Walls

In RC buildings, shear walls are considered as one of the critical elements in resisting lateral loads. Sakr et al. [109] numerically investigated the behaviour of UHPFRC and reinforced UHPFRC-strengthened RC shear walls under lateral loading using 2D finite element models. The proposed finite element models were validated with existing experimental data and the effectiveness of UHPFRC strengthening of shear walls was compared with that of shear walls strengthened by externally bonded carbon fibre-reinforced polymer sheets. The numerical model results showed that a UHPFRC jacket with a thickness of 25 mm improved the diagonal tension shear strength of the reference RC walls with poor concrete quality and confinement. A UHPFRC jacket complemented with a steel mesh limited the crack opening and subsequently significantly enhanced the lateral drift. UHPFRC and reinforced UHPFRC-strengthened RC shear walls exhibited an increase in ultimate resistance of up to 96% and 162%, respectively, compared to the reference RC wall. UHPFRC strengthening of RC walls was found to be effective in comparison with carbon fibre-reinforced polymer strengthening considering the aspects of higher strength, ductility, durability and fracture toughness. In addition, it was found that the behaviour of RC walls can be further improved if the jacket was better connected to the footing.

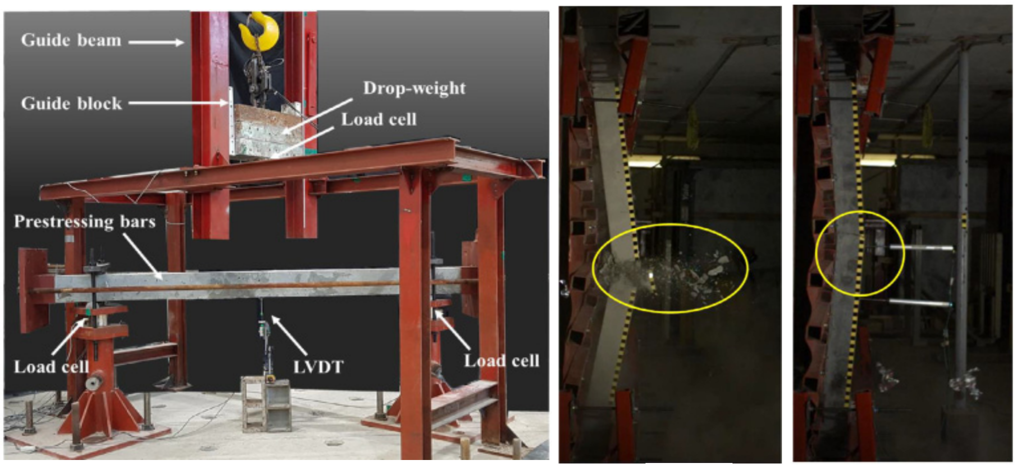
Franssen et al. [110] tested shear-critical RC wall panels strengthened with UHPFRC jackets. Four large-scale wall panel specimens were considered for the testing programme, including reference panels without strengthening. The level of axial load, the jacket thickness and the method of concrete surface preparation were varied during the experiments. Surface preparation techniques enhanced the bonding capacity between the UHPFRC layer and the RC substrate. Specimens with rough water-jetted surfaces did not exhibit debonding failure, whereas specimens with smooth surfaces were susceptible to debonding. The shear capacities of UHPFRC-strengthened RC walls after rough surface preparation with 30-mm- and 50-mm-thick jackets were 1166 and 1466 kN, respectively, compared to the 1043 kN capacity of the reference specimen. The reference wall panel without UHPFRC strengthening exhibited shear brittle failure, whereas the strengthened specimens with 30 and 50 mm UHPFRC jackets showed flexural failure while exhibiting better crack control. Furthermore, a three-degree-of-freedom kinematic model was proposed and validated, which was capable of accurately predicting the deformation patterns of UHPFRC-strengthened wall panels. This model provided an understanding of the shear-resisting mechanism of retrofitted RC wall panels.

It is evident from the previous studies that UHPFRC jacketing is effective for the shear strengthening of RC structural components. The shear strengthening procedure resulted in avoiding the brittle shear failure of shear deficient components, allowing them to reach the flexural capacity. In addition to the enhanced strength characteristics from shear strengthening via UHPFRC jacketing, the crack control, durability, ductility and fracture toughness are improved.

4.4. Impact Resistance and Torsional Strengthening

During their service life, RC members can be subjected to dynamic loadings from earthquakes, blasts and impacts, leading to structural failure. Except for the conventional RC structures, blast and impact loading is of great interest in the protective design of structures in military applications. Considering these aspects, the impact resistance of UHPFRC-strengthened structures have been investigated. Fan et al. [111] explored the impact-resistant performance of UHPFRC-strengthened columns by conducting drop-hammer impact tests. The effect of axial load and the configuration of UHPFRC strengthening on the impact resistance of columns was experimentally investigated. UHPFRC jacket configurations of a single jacket in the contact impact zone, two jackets distributed at the ends of the column and a combination of jackets in the contact zone and at the ends were considered. The experimental results illustrated that the local damage around the impact hammer can be substantially mitigated due to the superior mechanical performance of the UHPFRC jacket. The presence of axial load improved the impact resistance of the strengthened columns due to the compressive membrane action. Considering different jacket configurations, the best performance was observed for the strengthened column with two end UHPFRC jackets in the potential plastic hinge zone of the column. However, the worst performance was observed in the configuration of the strengthened specimen with three jackets, where brittle shear failure was triggered in the remaining RC region.

A similar study was carried out by Lee et al. [112] to investigate the impact and blast resistance of RC columns. Six large-scale columns were tested in the experimental programme, which were retrofitted with UHPFRC layers. Both drop-weight impact and shock tube tests were conducted. In addition, numerical models were also developed using non-linear finite element simulations to predict the experimental response. Figure 11a illustrates the drop-weight impact test set-up used to evaluate the impact performance of the strengthened columns. Figure 11b,c shows the blast fragments of a normal strength RC column and a UHPFRC retrofitted column, respectively. The use of UHPFRC jacketing along with seismic detailing of columns leads to significant improvements in the blast and impact resistance, reducing the maximum and residual displacements. Furthermore, an increased lateral load carrying capacity and better crack control was exhibited by the strengthened columns under blast and impact loads.



(**a**) (**b**) (**c**)

Figure 11. Impact and blast loading. (**a**) Drop-weight impact test set up, (**b**) normal strength column performance at blast and (**c**) UHPFRC-strengthened column performance at blast ([112]—Elsevier Copyright).

The impact resistance of UHPFRC-strengthened beams was studied in [113]. Drop hammer impact tests were carried out for a series of UHPFRC retrofitted beams to evaluate the dynamic response and the failure modes. Strengthening configurations consisted of retrofitting UHPFRC layers to the tension surface, to both the tension and compression sides, and to the tension side with a 5 mm gap between interfaces. The beam specimen with a 15 mm UHPFRC layer at the tension face exhibited diagonal shear failure in the impact test, compared to concrete spalling observed for the control specimen. Decreases in the maximum and residual displacements were observed and these reductions were 9.1% and 25.3%, respectively. UHPFRC-strengthened beams with a gap in between the interfaces exhibited better impact resistance and reduced beam deflections. From the results of these experimental and numerical studies, it can be concluded that UHPFRC jacketing is capable of improving the impact and blast resistance of RC members considering the mode of failure, lateral load carrying capacity, crack control and the maximum and residual displacements.

Most of the research into UHPFRC retrofitting have focussed on the axial, flexural and shear capacity enhancement of RC members, along with impact resistance improvements. Torsional improvement is another aspect to be considered. Mohammed et al. [114] investigated the torsional enhancement of RC beams via UHPFRC strengthening. Ten beams consisting of only longitudinal reinforcement were strengthened with UHPFRC layers on two, three and four sides. The layer thickness was varied from 10 to 25 mm keeping the reinforcement ratio equal for all specimens. Retrofitted beams with UHPFRC layers on four sides exhibited better torsional behaviour and a higher capacity than the strengthened beams on two and three sides. Four-side-strengthened beams exhibited a maximum increase in the cracking and ultimate torques of 95% and 267%, respectively, in comparison with the reference specimen. It was also observed that the UHPFRC contribution to the torsional strength increased with the increase in layer thickness.

5. Results and Discussion

5.1. Mechanical Properties

From experimental results, it has been observed that as the water/cement ratio decreases, the compressive strength of UHPFRC increases. However, the size effect has to be considered in determining the compressive and tensile strengths. Experimental results have indicated that smaller samples possess higher compressive strengths; thus, the size effect of UHPFRC specimens is significant in the context of the compressive strength. The compressive strength of UHPFRC is partly governed by the effect of pre-treatment. Thermally treated UHPFRC specimens possess a higher 28-day compressive strength compared to that of air-treated specimens. In addition to heat treatment, the application of a confining pressure during the setting of UHPFRC increases the compactness and thereby positively influences the compressive strength. With the increase in the steel fibre volume fraction, the failure mode of specimens changes from sudden explosive failure to more representative of ductile failure, where the UHPFRC specimen was intact without chipping and spalling. Previous research has shown that the addition of high doses of steel fibres does not significantly influence the compressive strength of UHPFRC. A negative impact of increasing the steel fibre concentration is fibre bundling, which can lead to weak spots, reducing the efficiency of fibres and the homogeneity of the mix. The effect of the steel fibre shape is paramount for compressive strength enhancement. The compressive strength of a UHPFRC mix increases in the order of straight fibres, hooked end fibres and corrugated fibres, respectively.

It was found that the cracking, peak flexural tensile strength and the strain hardening behaviour were improved by the addition of steel fibres into the UHPC matrix. A linear increase in flexural tensile strength was observed with the increase in the fibre volume ratio. However, it was observed that the increase in the fibre content had little effect on the first crack strength and the first crack deflection. Furthermore, the upper limit of the fibre volume ratio needs to be determined by considering fibre bundling. Blending of fibres in the UHPFRC mix enhanced the tensile behaviour. The addition of micro-fibres into the hybrid system enhanced both the strain hardening and multiple cracking behaviour. Similar to the compressive strength, smaller specimen sizes exhibited increased flexural strengths.

5.2. Structural Retrofitting

All the flexural retrofitting configurations led to higher stiffness and increased resistance while delaying crack propagation. For four-point bending tests, significant improvements in the ultimate loads were observed. The addition of reinforcing bars to the UHPFRC layer further increased the composite members' hardening magnitude and substantially delayed the formation of localised macro-cracks. Experimental and analytical results indicated an increase in flexural capacity with the increase in UHPFRC thickness. In addition to in situ casting, precast UHPFRC strips can be externally bonded to achieve flexural capacity enhancements. However, the main disadvantage identified in this strengthening process was the higher quality control and workmanship required in fabricating and bonding laminates. Beams strengthened on three sides exhibited the highest moment capacity enhancement in comparison with the other retrofitting configurations. The experimental results of three-point bending tests showed that the strengthening results in reduced diagonal cracking, while developing more flexural cracks. An improved ductile performance with deflection hardening was observed in the post-cracking stage, exhibiting good energy absorption.

Some structural members such as columns and piers are subjected to combined axial loads and moments. These elements can be strengthened with UHPFRC covers. UHPFRC retrofitting has been used to improve the seismic behaviour of bridge piers with insufficient seismic resilience. Proposed UHPFRC interventions specifically focus on the regions in the plastic hinge zone to improve the ductility and guarantee plastic seismic energy dissipation. Furthermore, jackets were effective in enhancing the piers' lateral load carrying capacity. Moreover, UHPFRC jackets improved the RC piers' self-centring capability while minimising the residual lateral drift. The results of the studies on the performance of UHPFRC-strengthened columns under eccentric loading indicated that the gain in moment capacity, axial load capacity and stiffness is inversely proportional to the eccentricity ratio and proportional to the UHPFRC jacket thickness. UHPFRC jacketing significantly enhanced the axial load carrying capacity, moment capacity, ductility, energy dissipation and crack control in RC columns. In addition, the blast and impact resistance were also improved by UHPFRC jacketing. Nevertheless, specific attention needs to be paid in determining the jacket height and thickness, the type of fibres used and the jacketing configuration, since these parameters have a substantial influence on the dynamic performance of UHPFRC-strengthened columns.

Previous studies have shown the suitability of UHPFRC strengthening to improve the shear capacity of structural members. Shear brittle failures are possible for beams with smaller span-to-depth ratios or structural components with deficient shear resistance. Most of the UHPFRC-strengthened beams avoided brittle shear failures. A UHPFRC layer significantly enhanced the shear strength of the specimens without compromising the deformation capacity. In addition to beams, the shear strengthening of RC slabs is important, especially considering the punching shear capacity. It was found that an increase in the UHPFRC overlay thickness to RC slab thickness ratio affects the enhancement in the punching shear strength. It was observed that the yield strength and rebar ratio of the UHPFRC layer did not have a significant effect on the punching shear capacity enhancement or on the ductility of the strengthened slab. It was concluded that the punching shear strength of a composite UHPFRC-RC flat slab is a function of thickness and the strength of the UHPFRC overlay.

Other than beams and slabs, RC shear walls can be retrofitted with UHPFRC. UHPFRC and reinforced UHPFRC-strengthened RC shear walls exhibited an increase in ultimate resistance. UHPFRC jackets complemented with steel mesh limited the crack opening and subsequently significantly enhanced the lateral drift. Surface preparation techniques enhanced the bonding capacity between the UHPFRC layer and the RC substrate. Specimens with rough water-jetted surfaces did not exhibit debonding failure, whereas specimens with smooth surfaces were susceptible to debonding. Shear strengthening procedures result in avoiding the brittle shear failure of shear deficient components and allows them to reach the flexural capacity. In addition to the enhanced strength characteristics from shear strengthening via UHPFRC jacketing, the aspects of crack control, durability, ductility and fracture toughness are improved.

Enhancement in the impact resistance is another crucial aspect which can be successfully addressed by UHPFRC strengthening. The impact resistance of UHPFRC-strengthened columns can be determined by conducting drop-hammer impact tests. Previous experimental results have illustrated that the local damage around the impact hammer can be substantially mitigated due to the superior mechanical performance of the UHPFRC jacket. The use of UHPFRC jacketing along with seismic detailing of columns leads to significant improvements in the blast and impact resistances, reducing the maximum and residual displacements. Furthermore, an increased lateral load carrying capacity and an improved crack control was exhibited by the strengthened columns under blast and impact loads.

6. Conclusions

UHPFRC possesses superior mechanical properties, along with an improved durability, ductility and workability; a low permeability; and a high abrasion resistance, impact resistance and fire resistance. Therefore, UHPFRC is identified as a cementitious composite suitable for rehabilitation and strengthening of RC structures. Retrofitting can be carried out on structurally deficient components and members subjected to severe environmental conditions and extreme loading. Experimental results have shown that UHPFRC strengthening is effective in improving the axial, shear, flexural and torsional capacities and the impact resistance of structural components. UHPFRC retrofitting substantially increases the load-carrying capacity and the stiffness of RC members, while providing a better cracking control. Both the epoxy bonding of prefabricated UHPFRC strips and the in situ instalment of UHPFRC layers around the member lead to a high bond strength between the UHPFRC overlay and the RC substrate. Nevertheless, surface preparation techniques (e.g., sandblasting) conducted on the parent concrete enhance the bond strength and avoid interface slipping.

The behaviour of retrofitted members relies on the strengthening configuration. RC members strengthened on all sides exhibit a monolithic behaviour, along with the largest improvements in load carrying capacity and stiffness compared to other configurations. However, there can be practical limitations in reaching all of the surfaces of existing structures. Therefore, the most suitable UHPFRC retrofitting configuration has to be selected considering the practical implications. Furthermore, the thickness of the UHPFRC overlay is directly proportional to the strength enhancement. Additional strength gain and hardening are achieved by the addition of reinforcing bars to the UHPFRC layer. Increasing the steel fibre content enhances the ductility and flexural strength of strengthened members. However, excessive fibre contents can result in fibre bundling, causing weak spots and affecting the homogeneity of the mix. The optimum fibre content for a typical UHPFRC mix was found to be around 2% by volume of the matrix. In addition, appropriate quality control should be ensured to retain the homogeneity of the mix, especially during the mixing stage. When compared with RC, UHPFRC requires proper workmanship to yield better outcomes. In addition to the fibre content, other factors such as fibre type, fibre geometry, fibre orientation and the fibre distribution are crucial in the performance of a UHPFRC mix. From the studies on the mechanical properties of UHPFRC, it can be concluded that larger specimens exhibit inferior mechanical strengths compared to smaller specimens. Numerical and analytical models have been developed to understand the behaviour of UHPFRC-strengthened composite members.

Future research should be directed towards developing design equations and guidelines for axial, flexural, shear and torsional strengthening of RC members using UHPFRC. The effect of UHPFRC strengthening under varying weather conditions such as freezing and thawing also needs to be thoroughly investigated. In addition, the corrosion of the surface of the steel fibres of the UHPFRC overlay is one of the main challenges facing UHPFRC strengthening, which needs to be addressed. Therefore, the initiation and progression of corrosion should be studied in detail to better understand the depletion in UHPFRC performance caused by corrosion.

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References

1. Neville, A. Chloride Attack of Reinforced Concrete: An Overview. *Mater. Struct.* **1995**, *28*, 63–70. [CrossRef]
2. Val, D.V.; Stewart, M.G. Reliability Assessment of Ageing Reinforced Concrete Structures—Current Situation and Future Challenges. *Struct. Eng. Int. J. Int. Assoc. Bridge Struct. Eng. (IABSE)* **2009**, *19*, 211–219. [CrossRef]
3. Kalra, R.; Neubauer, U. Strengthening of the West Gate Bridge with Carbon Fibre Composites—A Proof Engineer's Perspective. *Aust. J. Civ. Eng.* **2003**, *1*, 51–58. [CrossRef]
4. Raza, S.; Khan, M.K.I.; Menegon, S.J.; Tsang, H.H.; Wilson, J.L. Strengthening and Repair of Reinforced Concrete Columns by Jacketing: State-of-the-Art Review. *Sustainability* **2019**, *11*, 3208. [CrossRef]
5. Santarsiero, G.; Masi, A. Seismic Upgrading of RC Wide Beam–Column Joints Using Steel Jackets. *Buildings* **2020**, *10*, 203. [CrossRef]
6. Chalioris, C.; Kytinou, V.; Voutetaki, M.; Papadopoulos, N. Repair of Heavily Damaged RC Beams Failing in Shear Using U-Shaped Mortar Jackets. *Buildings* **2019**, *9*, 146. [CrossRef]
7. Abbas, H.; Ibrahim, S.M.; Al-Hazmi, N.; Elsanadedy, H.; Almusallam, T.; Al-Salloum, Y. Axial Compression Behavior of Wall-like Reinforced Concrete Columns Retrofitted Using Different FRP Schemes. *Buildings* **2022**, *13*, 26. [CrossRef]
8. Daly, A.F.; Witarnawan, I.W. Strengthening of Bridges Using External Post–Tensioning. In Proceedings of the 2nd Conference of Eastern Asia Society for Transportation Studies, Kuala Lumpur, Malaysia, 4–7 September 1997.
9. Al-Zu'bi, M.; Fan, M.; Anguilano, L. Advances in Bonding Agents for Retrofitting Concrete Structures with Fibre Reinforced Polymer Materials: A Review. *Constr. Build. Mater.* **2022**, *330*, 127115. [CrossRef]
10. Nayak, A.N.; Kumari, A.; Swain, R.B. Strengthening of RC Beams Using Externally Bonded Fibre Reinforced Polymer Composites. *Structures* **2018**, *14*, 137–152. [CrossRef]
11. Jirawattanasomkul, T.; Likitlersuang, S.; Wuttiwannasak, N.; Ueda, T.; Zhang, D.; Shono, M. Structural Behaviour of Pre-Damaged Reinforced Concrete Beams Strengthened with Natural Fibre Reinforced Polymer Composites. *Compos. Struct.* **2020**, *244*, 112309. [CrossRef]
12. Bisby, L.A. *Fire Behaviour of Fibre-Reinforced Polymer (FRP) Reinforced or Confined Concrete*; Queen's University: Kingston, ON, Canada, 2003.
13. Eide, M.B.; Hisdal, J.M. *Ultra High Performance Fibre Reinforced Concrete (UHPFRC)–State of the Art*; Blindern: Oslo, Norway, 2012.
14. Richard, P.; Cheyrezy, M. Composition of Reactive Powder Concretes. *Cem. Concr. Res.* **1995**, *25*, 1501–1511. [CrossRef]
15. Rossi, P.; Arca, A.; Parant, E.; Fakhri, P. Bending and Compressive Behaviours of a New Cement Composite. *Cem. Concr. Res.* **2005**, *35*, 27–33. [CrossRef]
16. Tayeh, B.A.; Abu Bakar, B.H.; Megat Johari, M.A.; Voo, Y.L. Evaluation of Bond Strength between Normal Concrete Substrate and Ultra High Performance Fiber Concrete as a Repair Material. *Proc. Procedia Eng.* **2013**, *54*, 554–563. [CrossRef]
17. Rossi, P. Ultra-High Performance Fiber-Reinforced Concretes. *Concr. Int.* **2001**, *23*, 46–52.
18. Habel, K. *Structural Behaviour of Elements Combining Ultra-High Performance Fibre Reinforced Concretes (Uhpfrc) and Reinforced Concrete*; EPEL: Lausanne, Switzerland, 2004; Volume 3036.
19. Deeb, R.; Ghanbari, A.; Karihaloo, B.L. Development of Self-Compacting High and Ultra High Performance Concretes with and without Steel Fibres. *Cem. Concr. Compos.* **2012**, *34*, 185–190. [CrossRef]
20. Al-Osta, M.A. Exploitation of Ultrahigh-Performance Fibre-Reinforced Concrete for the Strengthening of Concrete Structural Members. *Adv. Civ. Eng.* **2018**, *2018*, 1–12. [CrossRef]
21. Abbas, S.; Nehdi, M.L.; Saleem, M.A. Ultra-High Performance Concrete: Mechanical Performance, Durability, Sustainability and Implementation Challenges. *Int. J. Concr. Struct. Mater.* **2016**, *10*, 271–295. [CrossRef]
22. de Larrard, F.; Sedran, T. Mixture-Proportioning of High-Performance Concrete. *Cem. Concr. Res.* **2002**, *32*, 1699–1704. [CrossRef]
23. Yu, R.; Spiesz, P.; Brouwers, H.J.H. Mix Design and Properties Assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). *Cem. Concr. Res.* **2014**, *56*, 29–39. [CrossRef]
24. Ge, Z.; Wang, K.; Sun, R.; Huang, D.; Hu, Y. Properties of Self-Consolidating Concrete Containing Nano-$CaCO_3$. *J. Sustain. Cem. Based Mater.* **2014**, *3*, 191–200. [CrossRef]
25. vande Voort, T.L. *Design and Field Testing of Tapered H-Shaped Ultra High Performance Concrete Piles*; Iowa State University ProQuest Dissertations Publishing: Iowa, IA, USA, 2008.
26. Camacho, E.; López, J.Á.; Ros, P.S. Definition of Three Levels of Performance for UHPFRC-VHPFRC with Available Materials. In Proceedings of the Hipermat 2012—3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials, Kassel, German, 7–12 March 2012.
27. Graybeal, B.; Davis, M. Cylinder or Cube: Strength Testing of 80 to 200 MPa (11.6 to 29 Ksi) Ultra-High-Performance Fiber-Reinforced Concrete. *ACI Mater. J.* **2008**, *105*, 603. [CrossRef]
28. Kazemi, S.; Kazemi, S. Influence of Specimen Size and Fiber Content on Mechanical Properties of Ultra-High-Performance Fiber-Reinforced Concrete. *ACI Mater. J.* **2012**, *109*. [CrossRef]
29. Shaikh, F.U.A.; Luhar, S.; Arel, H.Ş.; Luhar, I. Performance Evaluation of Ultrahigh Performance Fibre Reinforced Concrete—A Review. *Constr. Build. Mater.* **2020**, *232*, 117152. [CrossRef]

30. Hassan, A.M.T.; Jones, S.W.; Mahmud, G.H. Experimental Test Methods to Determine the Uniaxial Tensile and Compressive Behaviour of Ultra High Performance Fibre Reinforced Concrete(UHPFRC). *Constr. Build. Mater.* **2012**, *37*, 874–882. [CrossRef]
31. Spasojevic, A.; Redaelli, D.; Fernández Ruiz, M.; Muttoni, A. Influence of Tensile Properties of UHPFRC on Size Effect in Bending. In Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, German, 5–7 March 2008.
32. Wille, K.; Parra-Montesinos, G.J. Effect of Beam Size, Casting Method, and Support Conditions on Flexural Behavior of Ultra-High-Performance Fiber-Reinforced Concrete. *ACI Mater. J.* **2012**, *109*. [CrossRef]
33. Mahmud, G.H.; Yang, Z.; Hassan, A.M.T. Experimental and Numerical Studies of Size Effects of Ultra High Performance Steel Fibre Reinforced Concrete (UHPFRC) Beams. *Constr. Build. Mater.* **2013**, *48*, 1027–1034. [CrossRef]
34. Graybeal, B.A. *Material Property Characterization of Ultra-High Performance Concrete*; FHWA-HRT-06-103; U.S. Federal Highway Administration. Office of Infrastructure Research and Development: Washington, DC, USA, 2006.
35. Ahlborn, T.M.; Misson, D.L.; Peuse, E.J.; Gilbertson, C.G.; Fehling, E. Durability and Strength Characterization of Ultra-High Performance Concrete under Variable Curing Regimes. In Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, 5–7 March 2008.
36. Reda, M.M.; Shrive, N.G.; Gillott, J.E. Microstructural Investigation of Innovative UHPC. *Cem. Concr. Res.* **1999**, *29*, 323–329. [CrossRef]
37. Schmidt, M.; Fehling, E.; Teichmann, T.; Kai, B.; Roland, B. Ultra-High Performance Concrete: Perspective for the Precast Concrete Industry. *Betonw. Und Fert.-Tech. /Concr. Precast. Plant. Technol.* **2003**, *69*, 16–29.
38. El-Dieb, A.S. Mechanical, Durability and Microstructural Characteristics of Ultra-High-Strength Self-Compacting Concrete Incorporating Steel Fibers. *Mater. Des.* **2009**, *30*, 4286–4292. [CrossRef]
39. Abbas, S.; Soliman, A.M.; Nehdi, M.L. Exploring Mechanical and Durability Properties of Ultra-High Performance Concrete Incorporating Various Steel Fiber Lengths and Dosages. *Constr. Build. Mater.* **2015**, *75*, 429–441. [CrossRef]
40. Magureanu, C.; Sosa, I.; Negrutiu, C.; Heghes, B. Mechanical Properties and Durability of Ultra-High-Performance Concrete. *ACI Mater. J.* **2012**, *109*, 177–183.
41. Wu, Z.; Shi, C.; He, W.; Wu, L. Effects of Steel Fiber Content and Shape on Mechanical Properties of Ultra High Performance Concrete. *Constr. Build. Mater.* **2016**, *103*, 8–14. [CrossRef]
42. Park, S.H.; Kim, D.J.; Ryu, G.S.; Koh, K.T. Tensile Behavior of Ultra High Performance Hybrid Fiber Reinforced Concrete. *Cem. Concr. Compos.* **2012**, *34*, 172–184. [CrossRef]
43. van Tuan, N.; Ye, G.; van Breugel, K.; Fraaij, A.L.A.; Bui, D.D. The Study of Using Rice Husk Ash to Produce Ultra High Performance Concrete. *Constr. Build. Mater.* **2011**, *25*, 2030–2035. [CrossRef]
44. van Tuan, N.; Ye, G.; van Breugel, K.; Copuroglu, O. Hydration and Microstructure of Ultra High Performance Concrete Incorporating Rice Husk Ash. *Cem. Concr. Res.* **2011**, *41*, 1104–1111. [CrossRef]
45. Vejmelková, E.; Keppert, M.; Rovnaníková, P.; Ondráček, M.; Keršner, Z.; Černý, R. Properties of High Performance Concrete Containing Fine-Ground Ceramics as Supplementary Cementitious Material. *Cem. Concr. Compos.* **2012**, *34*, 55–61. [CrossRef]
46. Yu, R.; Spiesz, P.; Brouwers, H.J.H. Development of an Eco-Friendly Ultra-High Performance Concrete (UHPC) with Efficient Cement and Mineral Admixtures Uses. *Cem. Concr. Compos.* **2015**, *55*, 383–394. [CrossRef]
47. Yang, S.L.; Millard, S.G.; Soutsos, M.N.; Barnett, S.J.; Le, T.T. Influence of Aggregate and Curing Regime on the Mechanical Properties of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). *Constr. Build. Mater.* **2009**, *23*, 2291–2298. [CrossRef]
48. Aldahdooh, M.A.A.; Muhamad Bunnori, N.; Megat Johari, M.A. Evaluation of Ultra-High-Performance-Fiber Reinforced Concrete Binder Content Using the Response Surface Method. *Mater. Des.* **2013**, *52*, 957–965. [CrossRef]
49. Wille, K.; El-Tawil, S.; Naaman, A.E. Properties of Strain Hardening Ultra High Performance Fiber Reinforced Concrete (UHP-FRC) under Direct Tensile Loading. *Cem. Concr. Compos.* **2014**, *48*, 53–66. [CrossRef]
50. Magureanu, C.; Sosa, I.; Negrutiu, C.; Heghes, B. Physical and Mechanical Properties of Ultra High Strength Fiber Reinforced Cementitious Composites. *Korea Concr. Inst.* **2010**, 1491–1497.
51. Yoo, D.Y.; Lee, J.H.; Yoon, Y.S. Effect of Fiber Content on Mechanical and Fracture Properties of Ultra High Performance Fiber Reinforced Cementitious Composites. *Compos. Struct.* **2013**, *106*, 742–753. [CrossRef]
52. Kang, S.T.; Lee, Y.; Park, Y.D.; Kim, J.K. Tensile Fracture Properties of an Ultra High Performance Fiber Reinforced Concrete (UHPFRC) with Steel Fiber. *Compos. Struct.* **2010**, *92*, 61–71. [CrossRef]
53. Eldin, H.K.S.; Mohamed, H.A.; Khater, M.; Ahmed, S. Mechanical Properties of Ultra-High Performance Fiber Reinforced Concrete. *Int. J. Eng. Innov. Technol.* **2014**, *4*.
54. Kang, S.T.; Lee, B.Y.; Kim, J.K.; Kim, Y.Y. The Effect of Fibre Distribution Characteristics on the Flexural Strength of Steel Fibre-Reinforced Ultra High Strength Concrete. *Constr. Build. Mater.* **2011**, *25*, 2450–2457. [CrossRef]
55. Yoo, D.Y.; Kang, S.T.; Yoon, Y.S. Effect of Fiber Length and Placement Method on Flexural Behavior, Tension-Softening Curve, and Fiber Distribution Characteristics of UHPFRC. *Constr. Build. Mater.* **2014**, *64*, 67–81. [CrossRef]
56. Nguyen, D.L.; Kim, D.J.; Ryu, G.S.; Koh, K.T. Size Effect on Flexural Behavior of Ultra-High-Performance Hybrid Fiber-Reinforced Concrete. *Compos. B Eng.* **2013**, *45*, 1104–1116. [CrossRef]
57. Frettlöhr, B.; Reineck, K.H.; Reinhardt, H.W. Size and Shape Effect of Uhpfrc Prisms Tested under Axial Tension and Bending. *RILEM Bookseries* **2012**, *6*, 365–372. [CrossRef]

58. Yang, I.H.; Joh, C.; Kim, B.S. Structural Behavior of Ultra High Performance Concrete Beams Subjected to Bending. *Eng. Struct.* **2010**, *32*, 3478–3487. [CrossRef]
59. Habel, K.; Gauvreau, P. Response of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) to Impact and Static Loading. *Cem. Concr. Compos.* **2008**, *30*, 938–946. [CrossRef]
60. Yoo, D.Y.; Banthia, N.; Kim, S.W.; Yoon, Y.S. Response of Ultra-High-Performance Fiber-Reinforced Concrete Beams with Continuous Steel Reinforcement Subjected to Low-Velocity Impact Loading. *Compos. Struct.* **2015**, *126*, 233–245. [CrossRef]
61. Máca, P.; Sovják, R.; Konvalinka, P. Mix Design of UHPFRC and Its Response to Projectile Impact. *Int. J. Impact Eng.* **2014**, *63*, 158–163. [CrossRef]
62. Nicolaides, D.; Kanellopoulos, A.; Savva, P.; Petrou, M. Experimental Field Investigation of Impact and Blast Load Resistance of Ultra High Performance Fibre Reinforced Cementitious Composites (UHPFRCCs). *Constr. Build. Mater.* **2015**, *95*, 566–574. [CrossRef]
63. Sovják, R.; Vavřiník, T.; Zatloukal, J.; Máca, P.; Mičunek, T.; Frydrýn, M. Resistance of Slim UHPFRC Targets to Projectile Impact Using In-Service Bullets. *Int. J. Impact Eng.* **2015**, *76*, 166–177. [CrossRef]
64. Feng, J.; Sun, W.; Liu, Z.; Cui, C.; Wang, X. An Armour-Piercing Projectile Penetration in a Double-Layered Target of Ultra-High-Performance Fiber Reinforced Concrete and Armour Steel: Experimental and Numerical Analyses. *Mater. Des.* **2016**, *102*, 131–141. [CrossRef]
65. Charron, J.P.; Denarié, E.; Brühwiler, E. Permeability of Ultra High Performance Fiber Reinforced Concretes (UHPFRC) under High Stresses. *Mater. Struct. /Mater. Et Constr.* **2007**, *40*, 269–277. [CrossRef]
66. Wang, W.; Liu, J.; Agostini, F.; Davy, C.A.; Skoczylas, F.; Corvez, D. Durability of an Ultra High Performance Fiber Reinforced Concrete (UHPFRC) under Progressive Aging. *Cem. Concr. Res.* **2014**, *55*, 1–13. [CrossRef]
67. Matos, A.M.; Chaves Figueiredo, S.; Nunes, S.; Schlangen, E.; Barroso-Aguiar, J.L. Durability of an UHPFRC under Mechanical and Chloride Loads. *Constr. Build. Mater.* **2021**, *311*, 125223. [CrossRef]
68. Kang, S.T.; Kim, J.H.; Lee, B.Y. Effects of Water Reducing Admixture on Rheological Properties, Fiber Distribution, and Mechanical Behavior of UHPFRC. *Appl. Sci.* **2018**, *9*, 29. [CrossRef]
69. Farzad, M.; Shafieifar, M.; Azizinamini, A. Experimental and Numerical Study on Bond Strength between Conventional Concrete and Ultra High-Performance Concrete (UHPC). *Eng. Struct.* **2019**, *186*, 297–305. [CrossRef]
70. Jafarinejad, S.; Rabiee, A.; Shekarchi, M. Experimental Investigation on the Bond Strength between Ultra High Strength Fiber Reinforced Cementitious Mortar & Conventional Concrete. *Constr. Build. Mater.* **2019**, *229*, 116814. [CrossRef]
71. Alaee, F.J.; Karihaloo, B.L. Retrofitting of Reinforced Concrete Beams with CARDIFRC. *J. Compos. Constr.* **2003**, *7*, 174–186. [CrossRef]
72. Habel, K.; Denarié, E.; Brühwiler, E. Structural Response of Elements Combining Ultrahigh-Performance Fiber-Reinforced Concretes and Reinforced Concrete. *J. Struct. Eng.* **2006**, *132*, 1793–1800. [CrossRef]
73. Habel, K.; Denarié, E.; Brühwiler, E. Experimental Investigation of Composite Ultra-High-Performance Fiber-Reinforced Concrete and Conventional Concrete Members. *ACI Struct. J.* **2007**, *104*, 93. [CrossRef]
74. Noshiravani, T.; Brühwiler, E. Experimental Investigation on Reinforced Ultra-High-Performance Fiber-Reinforced Concrete Composite Beams Subjected to Combined Bending and Shear. *ACI Struct. J.* **2013**, *110*, 251–261. [CrossRef]
75. Lampropoulos, A.P.; Paschalis, S.A.; Tsioulou, O.T.; Dritsos, S.E. Strengthening of Existing Reinforced Concrete Beams Using Ultra High Performance Fibre Reinforced Concrete. In Proceedings of the 4th International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR, Leipzig, Germany, 5–7 October 2015.
76. Safdar, M.; Matsumoto, T.; Kakuma, K. Flexural Behavior of Reinforced Concrete Beams Repaired with Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). *Compos. Struct.* **2016**, *157*, 448–460. [CrossRef]
77. Aldahdooh, M.A.A.; Muhamad Bunnori, N.; Megat Johari, M.A.; Jamrah, A.; Alnuaimi, A. Retrofitting of Damaged Reinforced Concrete Beams with a New Green Cementitious Composites Material. *Compos. Struct.* **2016**, *142*, 27–34. [CrossRef]
78. Tanarslan, H.M. Flexural Strengthening of RC Beams with Prefabricated Ultra High Performance Fibre Reinforced Concrete Laminates. *Eng. Struct.* **2017**, *151*, 337–348. [CrossRef]
79. Tanarslan, H.M.; Alver, N.; Jahangiri, R.; Yalçınkaya; Yazıcı, H. Flexural Strengthening of RC Beams Using UHPFRC Laminates: Bonding Techniques and Rebar Addition. *Constr. Build. Mater.* **2017**, *155*, 45–55. [CrossRef]
80. Al-Osta, M.A.; Isa, M.N.; Baluch, M.H.; Rahman, M.K. Flexural Behavior of Reinforced Concrete Beams Strengthened with Ultra-High Performance Fiber Reinforced Concrete. *Constr. Build. Mater.* **2017**, *134*, 279–296. [CrossRef]
81. Dagenais, M.-A.; Massicotte, B. Cyclic Behavior of Lap Splices Strengthened with Ultrahigh Performance Fiber-Reinforced Concrete. *J. Struct. Eng.* **2017**, *143*, 04016163. [CrossRef]
82. Sadouki, H.; Denarié, E.; Brühwiler, E. Validation of a FEA Model of Structural Response of RC-Cantilever Beams Strengthened with a (R-) UHPFRC Layer. *Constr. Build. Mater.* **2017**, *140*, 100–108. [CrossRef]
83. Paschalis, S.A.; Lampropoulos, A.P.; Tsioulou, O. Experimental and Numerical Study of the Performance of Ultra High Performance Fiber Reinforced Concrete for the Flexural Strengthening of Full Scale Reinforced Concrete Members. *Constr. Build. Mater.* **2018**, *186*, 351–366. [CrossRef]
84. Ramachandra Murthy, A.; Karihaloo, B.L.; Priya, D.S. Flexural Behavior of RC Beams Retrofitted with Ultra-High Strength Concrete. *Constr. Build. Mater.* **2018**, *175*, 815–824. [CrossRef]

85. Ramachandra Murthy, A.; Karihaloo, B.L.; Vindhya Rani, P.; Shanmuga Priya, D. Fatigue Behaviour of Damaged RC Beams Strengthened with Ultra High Performance Fibre Reinforced Concrete. *Int. J. Fatigue* **2018**, *116*, 659–668. [CrossRef]
86. Yin, H.; Teo, W.; Shirai, K. Experimental Investigation on the Behaviour of Reinforced Concrete Slabs Strengthened with Ultra-High Performance Concrete. *Constr. Build. Mater.* **2017**, *155*, 463–474. [CrossRef]
87. Brühwiler, E. UHPFRC Technology to Enhance the Performance of Existing Concrete Bridges. *Struct. Infrastruct. Eng.* **2020**, *16*, 94–105. [CrossRef]
88. Brühwiler, E.; Bastien-Masse, M.; Mühlberg, H.; Houriet, B.; Fleury, B.; Cuennet, S.; Schär, P.; Boudry, F.; Maurer, M. Strengthening the Chillon Viaducts Deck Slabs with Reinforced UHPFRC. In Proceedings of the IABSE Conference, Geneva 2015: Structural Engineering: Providing Solutions to Global Challenges—Report, Geneva, Switzerland, 23–25 September 2015.
89. Moreillon, L.; Menétrey, P. Rehabilitation and Strengthening of Existing RC Structures with UHPFRC: Various Applications. In Proceedings of the RILEM-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete, Montpellier, France, 2–4 October 2017; RILEM Publication SARL: Montpellier, France, 2013; pp. 127–136.
90. Tong, T.; Yuan, S.; Zhuo, W.; He, Z.; Liu, Z. Seismic Retrofitting of Rectangular Bridge Piers Using Ultra-High Performance Fiber Reinforced Concrete Jackets. *Compos. Struct.* **2019**, *228*, 111367. [CrossRef]
91. Massicotte, B.; Dagenais, M.A.; Garneau, J.F. Bridge Pier Seismic Strengthening Using UHPFRC Cover. In Proceedings of the 9th International Conference on Short and Medium Span Bridges, Calgary, AB, Canada, 15–18 July 2014.
92. Dagenais, M.-A.; Massicotte, B.; Boucher-Proulx, G. Seismic Retrofitting of Rectangular Bridge Piers with Deficient Lap Splices Using Ultrahigh-Performance Fiber-Reinforced Concrete. *J. Bridge. Eng.* **2018**, *23*, 04017129. [CrossRef]
93. Lavorato, D.; Bergami, A.V.; Nuti, C.; Briseghella, B.; Xue, J.; Tarantino, A.M.; Marano, G.C.; Santini, S. Ultra-High-Performance Fibre-Reinforced Concrete Jacket for the Repair and the Seismic Retrofitting of Italian and Chinese RC Bridges. In Proceedings of the COMPDYN 2017—6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rhodes Island, Greece, 15–17 June 2017; Volume 1.
94. Zhou, M.; Lu, W.; Song, J.; Lee, G.C. Application of Ultra-High Performance Concrete in Bridge Engineering. *Constr. Build. Mater.* **2018**, *186*, 1256–1267. [CrossRef]
95. Tong, T.; Lei, H.; Yuan, S.; Liu, Z. Experimental Investigation and Seismic Vulnerability Assessment of Low Flexural Strength Rectangular Bridge Piers Retrofitted with Ultrahigh-Performance Concrete Jackets. *Eng. Struct.* **2020**, *206*, 110132. [CrossRef]
96. Sakr, M.A.; el Korany, T.M.; Osama, B. Analysis of RC Columns Strengthened with Ultra-High Performance Fiber Reinforced Concrete Jackets under Eccentric Loading. *Eng. Struct.* **2020**, *220*, 111016. [CrossRef]
97. Li, S.; Zhao, T.; Chu, C.; Wang, J.Q.; Shahria Alam, M.; Tong, T. Lateral Cyclic Response Sensitivity of Rectangular Bridge Piers Confined with UHPFRC Tube Using Fractional Factorial Design. *Eng. Struct.* **2021**, *235*, 111883. [CrossRef]
98. Elsayed, M.; Tayeh, B.A.; Elmaaty, M.A.; Aldahshoory, Y. Behaviour of RC Columns Strengthened with Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) under Eccentric Loading. *J. Build. Eng.* **2022**, *47*, 103857. [CrossRef]
99. Eshaghi-Milasi, S.; Mostofinejad, D.; Saljoughian, A.; Bahmani, H. Behavior of RC Columns Strengthened with UHPFRC Jackets through Grooving Method under Eccentric Loading: A Comparative Evaluation of Steel and Synthetic Macro Fibers in UHPFRC. *Struct. Concr.* **2022**, *23*, 187–206. [CrossRef]
100. Noshiravani, T.; Brühwiler, E. Behaviour of UHPFRC-RC Composite Beams Subjected to Combined Bending and Shear. In Proceedings of the 8th fib PhD Symposium. fib Symposium, Copenhagen, Denmark, 20–23 June 2010.
101. Meda, A.; Mostosi, S.; Riva, P. Shear Strengthening of Reinforced Concrete Beam with High-Performance Fiber-Reinforced Cementitious Composite Jacketing. *ACI Struct. J.* **2014**, *111*, 1059. [CrossRef]
102. Aghani, K.; Afshin, H. Experimental and Numerical Investigation on Shear Retrofitting of RC Beams by Prefabricated UHPFRC Sheets. *Civ. Eng. J.* **2016**, *2*, 168–179. [CrossRef]
103. Garg, V.; Bansal, P.P.; Sharma, R. Retrofitting of Shear-Deficient RC Beams Using UHP-FRC. *Iran. J. Sci. Technol.—Trans. Civ. Eng.* **2019**, *43*, 419–428. [CrossRef]
104. Zohrevand, P.; Yang, X.; Jiao, X.; Mirmiran, A. Punching Shear Enhancement of Flat Slabs with Partial Use of Ultrahigh-Performance Concrete. *J. Mater. Civ. Eng.* **2015**, *27*, 04014255. [CrossRef]
105. Bastien-Masse, M.; Brühwiler, E. Contribution of R-UHPFRC Strengthening Layers to the Shear Resistance of RC Elements. *Struct. Eng. Int.* **2016**, *26*, 365–374. [CrossRef]
106. Wu, X.; Yu, S.; Xue, S.; Kang, T.H.K.; Hwang, H.J. Punching Shear Strength of UHPFRC-RC Composite Flat Plates. *Eng. Struct.* **2019**, *184*, 278–286. [CrossRef]
107. Koo, I.-Y.; Hong, S.-G. Strengthening RC Columns with Ultra High Performance Concrete. In Proceedings of the 2016 Structures Congress, Jeju Island, Korea, 28 August–1 September 2016.
108. Hong, S.-G.; Lee, J.-H.; Choi, Y.; Gu, I.-Y. Seismic Strengthening of Concrete Columns by Ultrahigh-Performance Fiber-Reinforced Concrete Jacketing. *J. Struct. Eng.* **2021**, *147*, 04021157. [CrossRef]
109. Sakr, M.A.; El-khoriby, S.R.; Khalifa, T.M.; Nagib, M.T. Modeling of RC Shear Walls Strengthened with Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) Jackets. *Eng. Struct.* **2019**, *200*, 109696. [CrossRef]
110. Franssen, R.; Courard, L.; Mihaylov, B.I. Shear Behavior of Concrete Walls Retrofitted with Ultra- High-Performance Fiber-Reinforced Concrete Jackets. *ACI Struct. J.* **2021**, *118*. [CrossRef]
111. Fan, W.; Shen, D.; Yang, T.; Shao, X. Experimental and Numerical Study on Low-Velocity Lateral Impact Behaviors of RC, UHPFRC and UHPFRC-Strengthened Columns. *Eng. Struct.* **2019**, *191*, 509–525. [CrossRef]

112. Lee, J.Y.; Aoude, H.; Yoon, Y.S.; Mitchell, D. Impact and Blast Behavior of Seismically-Detailed RC and UHPFRC-Strengthened Columns. *Int. J. Impact Eng.* **2020**, *143*, 103628. [CrossRef]
113. Wei, J.; Li, J.; Wu, C.; Liu, Z.X.; Fang, J. Impact Resistance of Ultra-High Performance Concrete Strengthened Reinforced Concrete Beams. *Int. J. Impact Eng.* **2021**, *158*, 104023. [CrossRef]
114. Mohammed, T.J.; Abu Bakar, B.H.; Muhamad Bunnori, N. Torsional Improvement of Reinforced Concrete Beams Using Ultra High-Performance Fiber Reinforced Concrete (UHPFC) Jackets—Experimental Study. *Constr. Build. Mater.* **2016**, *106*, 533–542. [CrossRef]