Civil and Environmental Engineering
Vol. 21, Issue 2, 1326-1347, DOI: 10.2478/cee-2025-0097

STATE OF RESEARCH ON SHEAR STRENGTHENING / REPAIRING OF RC BEAMS WITH ULTRA-HIGH-PERFORMANCE CONCRETE (UHPC)

Ahmed SAFAA[1, *], Majid M.A. KADHIM[1]

[1] Department of Civil Engineering, University of Babylon, Hilla, Babil, Iraq.
[*] Corresponding author: ahmed.hamzah.engh379@student.uobabylon.edu.iq

Abstract

This paper presents a comprehensive review of recent research on the application of ultra-high-performance concrete (UHPC) layers for enhancing the shear strength of reinforced concrete (RC) beams. The first part of the paper presents a detailed literature review, culminating in a database of experimental tests on UHPC shear-strengthened RC beams. The analysis of the database reveals that UHPC overlays substantially enhance the shear capacity of RC beams. The experimental evidence shows that UHPC overlays demonstrated an increase in the shear strength of RC beams by up to 188%. Several key parameters, including the UHPC layer configuration, characteristics of the UHPC layer, bonding technique, and others, influence this strengthening method's effectiveness. Researchers have reported various failure modes, such as fibre fracture and detachment of the UHPC layer. Furthermore, observations suggest a potential interaction between the internal transverse steel reinforcement and the UHPC layer. The second part of this paper focuses specifically on the shear repair of RC beams using UHPC. The effectiveness of UHPC overlay repair techniques is significantly enhanced by a reinforced UHPC layer with FRP, which enhances its tensile characteristics. Finally, this research highlights current UHPC issues and recommends future work.

Keywords:

UHPC;
Shear;
RC beam;
Strengthening;
Repair.

1 Introduction

Many countries globally are facing a significant number of aging problems in their buildings and bridges, necessitating repair, strengthening, or replacement. In 2021, the American Society of Civil Engineers reported that 42% of United States bridges are at least 50 years old, and about 7.5% of US bridges are considered structurally deficient and require repair and strengthening [1]. Generally, reinforced concrete (RC) beams (or girders) should have adequate shear capacity to avoid the brittle shear failure mode. However, their shear capacity may become deficient due to increased design loads, deterioration in adverse environmental conditions, and structural upgrading to comply with the requirements of new design codes. Also, the shear capacity may become insufficient when flexural members need to be strengthened. Shear strengthening would then be necessary.

Several traditional methods have been used to repair and strengthen RC members, such as concrete and steel jacketing, external prestressing, and bonding of steel plates [2–8]. Even though these techniques significantly improve a structure's serviceability and ultimate limit states, they come with several disadvantages, such as an increase in the member's size and weight, high labour and equipment costs, and corrosion and debonding problems with steel plates. [9–11]. During the last two decades, bonding fibre-reinforced polymer (FRP) composites as a retrofitting system have become widely popular [12–17]. This system is cost-effective and easier to install than other options. It offers numerous benefits, including a high strength-to-weight ratio, excellent durability, and exceptional fatigue resistance [18, 19]. However, some problems that prevent this technology from being used to its full potential include brittle debonding failures, poor behaviour at high temperatures, and inapplicability on moist surfaces or at low temperatures [20–23]. This challenge prompted researchers to explore the use of advanced cementitious materials for repairing and strengthening concrete structural elements [24–26].

Recently, researchers have proposed fabric-reinforced cementitious matrix (FRCM) systems for repairing and strengthening concrete structures as an alternative to traditional techniques [27]. FRCM is a cementitious composite class consisting of different FRP products (e.g., dry fibre textiles or FRP grids) encased in a cementitious matrix. Numerous experimental tests have confirmed the efficacy of FRCM strengthening systems for shear strengthening of RC beams [28]. FRCM strengthening may offer an intriguing alternative due to its high-strength cementitious composites and dense fibre textile. However, debonding failure at the NSC-FRCM interface is still a common failure mode in the FRCM-strengthened concrete beams, which is mainly due to the high stiffness of the mortar with fibre textile and the limited bond strength between the strain-softening mortar and concrete [29–31]. A new class of high-performance fibre-reinforced cementitious composites (HPFRCCs), namely engineered cementitious composites (ECCs) was used as the matrix in FRCM, owing to its high durability, ductility, and energy absorption capacity [32–35]. It helps to fully utilise the high tensile strength of the FRP while overcoming the drawbacks of traditional FRCM's low ductility and poor crack resistance. However, ECCs' compressive strength is relatively low and close to that of conventional concrete [36].

As technology advanced, a new cement-based material called ultra-high-performance concrete (UHPC) was developed and attracted more attention. The mechanical properties of UHPC are significantly higher than those of traditional concrete. UHPC typically has a compressive and tensile strength of over 120 and 5 MPa, respectively [37, 38]. In addition to its high strength, UHPC has excellent durability and resistance to environmental factors such as freeze-thaw cycles, abrasion, and chemical attacks [39–42]. It has high ductility[43] and low permeability [44] making it less susceptible to water and chloride ion penetration, reducing the reinforcement's corrosion risk. The use of UHPC can significantly improve the performance of structures. Thus, the application of UHPC for new structures is increasing worldwide [45–49].

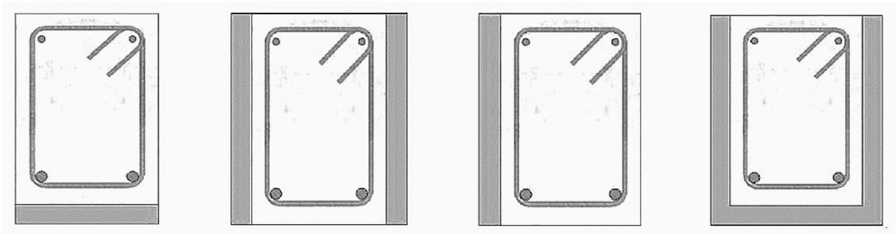
Based on its superior properties, researchers recently found that an emerging method for protecting, repairing, and strengthening concrete structures is to apply a thin overlay of ultra-high-performance fibre-reinforced concrete (UHPC) with or without reinforcement to existing RC members [50]. UHPC's strength in both compression and tension allows it to enhance a structure's capacity without significantly increasing its size. Moreover, unlike FRP and steel plates, which have a larger difference in modulus of elasticity compared to concrete, UHPC's smaller difference in modulus of elasticity compared to concrete and strong adherence and bond strength to concrete greatly reduce the occurrence of delamination between the repair layer and the concrete substrate. Furthermore, UHPC's superior durability makes it ideal for strengthening and repairing structures. Numerous experimental and numerical studies have been conducted in this field [51–60].

The use of UHPC for shear strengthening of reinforced concrete beams is a promising application that can significantly improve their performance and shear capacity [61–65]. However, due to the various countries in which UHPC has been developed, and its distinct characteristics, its effectiveness in strengthening and repairing existing RC beams can differ. Moreover, most of the available codes, such as AFGC [66], KICT [67], and JSCE [38] focus on the material properties characterisation and design of new UHPC. So, reviewing recent advancements in this innovative strengthening technique is necessary.

This paper summarizes the key findings and identifies the major issues that need to be covered in future studies on shear strengthening and repairing RC beams using UHPC. An extensive bibliographical survey of the literature on the shear strengthening of RC beams using UHPC is presented in the first section of this work. The effect of different parameters, including strengthening configuration, characteristics of the UHPC layer, bonding technique, and others, on the effectiveness of strengthening with UHPC is analysed. Different failure modes of the strengthened beams were also discussed. In the second part of this paper, a review of the literature on the shear repair of RC beams using UHPC is presented. Finally, additional research is recommended to further develop this promising method for shear strengthening and repair of existing RC beams.

2 Experimental databases for shear strengthening

UHPC has been applied in civil engineering structures and extended to various applications due to its outstanding properties. For instance, Wirojjanapirom et al. [68] studied the shear performance of RC beams using U-shaped UHPC permanent formwork. In the field of shear strengthening, thirteen articles were found in the literature related to shear strengthening of RC beams using UHPC overlay and are summarised in Table 1. The descriptions of the RC beams before strengthening, the characteristics of the UHPC overlay, and the experimental findings of UHPC-RC composite systems were compiled from these articles and are shown in Table A1 in Appendix A. Seventy-two strengthened beams are included in the database. These studies investigated the effect of UHPC layer thickness, steel fibre content, the bonding method, strengthening configurations, and other parameters on the shear capacity of RC beams. Typical shear-strengthening configurations are shown in Fig. 1.



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

Fig. 1: UHPC shear strengthening configurations (a) T-sided (tension side strengthening); (b) 2S (two lateral sides strengthening); (c) 1S (one lateral side strengthening); (d) U-shape (three sides strengthening).

Table 1: Summary of research on using UHPC overlay for shear strengthening of RC beams.

Reference	Year	Number of strengthened beams	Strengthening configuration [a]				Failure mode		
			T	U	2S	1S	Flexure [b]	Combined [c]	Shear [d]
[69]	2013	6	6				2	4	
[70]	2013	2			2		1		1 (1)
[71]	2015	3			3		1		2 (1)
[72]	2017	8			1	7			8
[73]	2019	4			2	2	2		2 (1)
[74]	2019	6		3	3		3	3	
[75]	2020	4	4						4 (4)
[63]	2021	5			5		3		2 (2)
[76]	2022	11		1	9	1	7	1	3 (2)
[64]	2022	3			3			1	2
[77]	2022	4			4				4
[61]	2023	12		6	6		12		
[78]	2023	4			4		3		1 (1)
	Total	72	10	10	42	10	34	9	29

a T= tensile side, U= U-shaped jacketing, 2S=2-sided, 1S=1-sided, b Yielding of longitudinal tensile steel bars and/or concrete crushing, c Failure mode related to combined flexural-shear crack with or without yielding of longitudinal tensile steel bars, d anchorage splitting failure, diagonal compression, diagonal tension with or without yielding of stirrups. Number in parentheses represents the number of tests failed in shear when debonding of UHPC overlay is observe.

2.1 Evaluation of the database and distribution of data

To evaluate the information collected in the database, the shear strength attributed to the UHPC overlay (V_{UHPC}) is calculated for each test. This is achieved by subtracting the shear strength of the corresponding control beam (V_{Con}) from the total measured shear strength of the strengthened beam. Although experimental beams aimed at investigating the shear behaviour of strengthened specimens are designed to achieve shear failure, it is essential to note that the addition of the UHPC overlay changed the failure mode from shear to flexural failure in many cases (see Table 1). Specimens that failed in flexure can be considered a lower bound of the strengthening capacity, but this paper does not further discuss the behaviour of beams that failed in that fashion. In Figs. 2-4 the ratio V_{UHPC}/V_{Con} varies according to the primary geometrical and mechanical characteristics of the strengthened beams and the UHPC overlay system. In these figures, the experimental data points are systematically subdivided according to their observed failure mechanism: flexural (F), combined flexural-shear (C), and shear (V). Furthermore, shear failures are differentiated based on the occurrence of UHPC layer detachment from the strengthened beam, denoted as V/D for cases with detachment. Section 2.4 presents a further discussion of failure modes.

Figs. 2-4 show that the increase in shear strength attributed to the UHPC overlay varies from 5% to 188%, with an average value of 54%. However, it is crucial to remember that the conclusions drawn in this article are based on the quantity and distribution of tests compiled in the database, and they should be confirmed when additional test results are made available.

2.1.1 Geometrical and mechanical properties of RC beams

Fig. 2 illustrates the variation of V_{UHPC}/V_{Con} ratio with the mechanical and geometrical characteristics of the beams, such as a/d (shear span to effective depth ratio), f'c (compressive strength of concrete), ρ_s (longitudinal steel reinforcement ratio defined as A_s/b_wd), and ρ_w (internal transverse steel reinforcement ratio defined as A_v/b_ws), where A_s represents the area of longitudinal steel reinforcement, b_w is the beam width, A_v represents the area of internal transverse steel reinforcement, and s is the spacing of the internal transverse steel reinforcement. Fig. 2 demonstrates that a/d ranges from 1 to 4.55, with most specimens (83%) having values between 2 and 3.5, which is typical for evaluating the shear strength of RC beams. Kani [79] shows that a/d ratios ranging from 2.5 to 3.0 correspond to the transition point between beam action and arch action, which also relates to the lowest values of shear strength in terms of average shear stress. Therefore, beams with values of a/d that fall within this range are typically utilised in the research to attain a lower bound for the shear strength. [74, 75] reported that as the shear-span (a/d) ratio grows, there is a corresponding decrease in the capacity improvement. However, no apparent relationship between V_{UHPC}/V_{Con} and a/d can be found for the range of a/d examined. On the other hand, beams with f'_c in the 19-30 MPa range represented 40% of all tests. The compressive strengths of many existing structures can be described well by these values of f'_c, which are relatively low for new constructions. As shown in Fig. 2, debonding failure dominates at low concrete compressive strength; this will be explained in Section 2.4.

67% of the tests were conducted on beams with a relatively high reinforcement ratio ($\rho_s > 0.02$). Although beams with large values of ρ_s are undesirable in real applications, their use is justified by the experimental objective of preventing flexural failure. As shown in Fig. 2, it is observed that a higher longitudinal reinforcement ratio or a lower transverse steel reinforcement ratio leads to dominant shear failure, as expected. Most tests (94%) were performed on beams with transverse steel reinforcement ($\rho_w \neq 0.0$). Unlike the previous variables, a possible relationship between V_{UHPC}/V_{Con} and ρ_w can be observed. A denser distribution of stirrups ($\rho_w > 0.003$) tends to reduce the efficiency of the UHPC overlay system. This behaviour can be explained by the possible interaction between the external strengthening UHPC layer and the interior transverse steel reinforcement, which has been reported for strengthening with FRP composites [80–82] and fibre-reinforced cementitious matrix (FRCM) [28, 52, 83]. In fact, to accurately estimate the shear strength of a strengthened beam, it has been reported that the interaction between external FRP reinforcement and internal steel reinforcement should be considered [15, 84]. According to [85], the maximum shear strength contributions of steel stirrups and FRP do not co-occur, suggesting that their combined effect may not be as high as the total sum of their values. The possible interaction between the external UHPC strengthening layer and the internal transverse reinforcement has also been reported by [64, 72], who witnessed that the strain values in the stirrups of the strengthened beams were lower than those of the control beams at the same load levels, which is similar to findings of [52, 83] for a beam strengthened with FRCM. Additionally, in the beams tested by [61], strengthening with UHPC overlay precluded the yielding of the stirrups; this phenomenon has also been reported for RC beams strengthening with FRP composites [86].

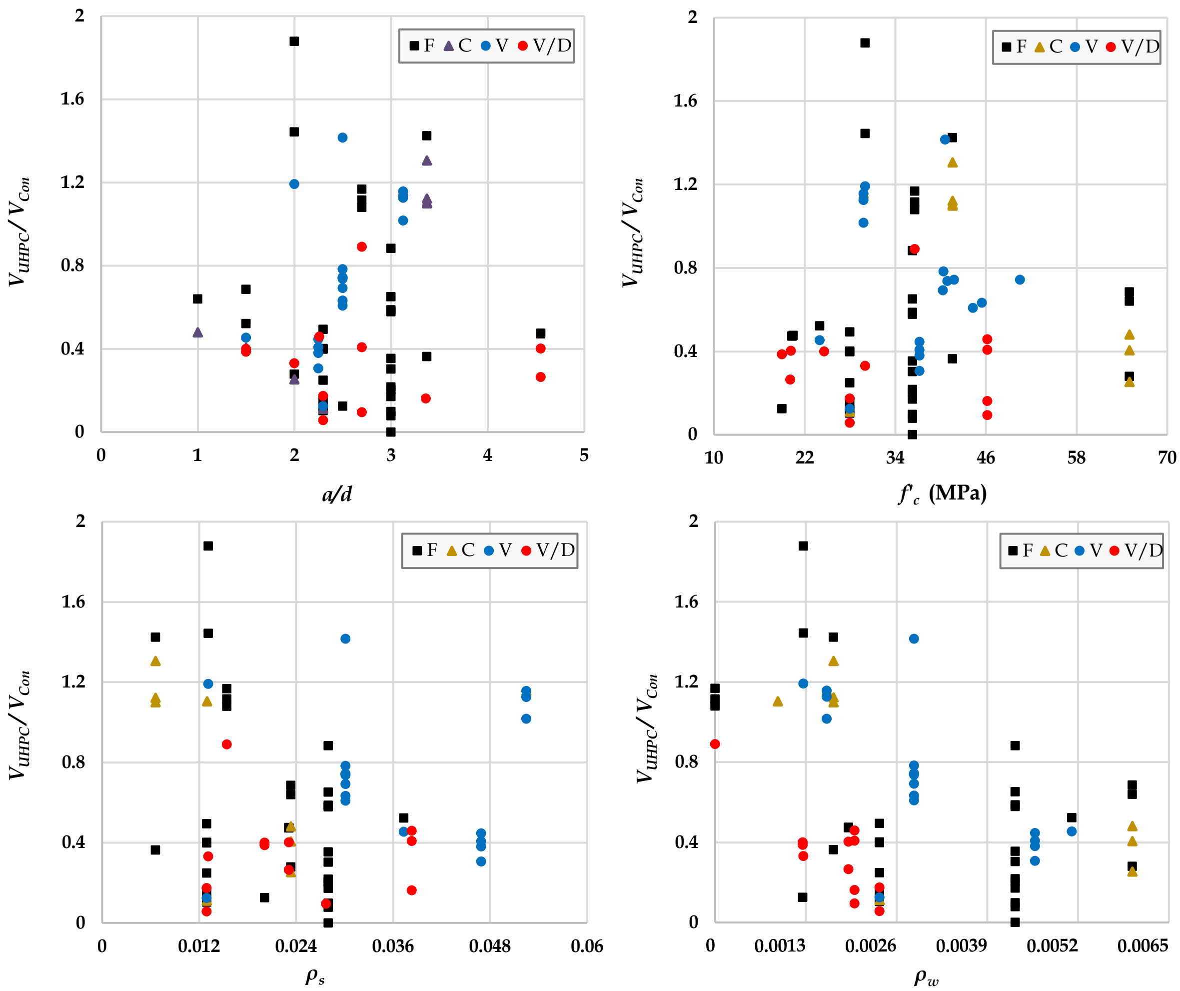


Fig. 2: Variation of V_{UHPC}/V_{Con} with a/d, f'c, ρ_s, and ρ_w.

2.1.2 Mechanical properties of UHPC

The influence of mechanical properties of the UHPC overlay (fibre volume ratio (V_f); UHPC tensile strength ($f_{t\text{-}UHPC}$); UHPC compressive strength (f'_{UHPC}); and UHPC modulus of elasticity (E_{UHPC})) on the V_{UHPC}/V_{Con} ratio is shown in Fig. 3. Theoretically, as more fibres bridge the shear crack, the shear capacity of a beam with fibre reinforcement will be increased [87]. According to Said et al. [76] increasing the ratio of steel fibre in the UHPC mixture improves the strength and ductility of the strengthened beams. However, based on the available data herein, the effect of the steel fibre content on the shear capacity of the tested specimens is unclear. Regarding the values of $f_{t\text{-}UHPC}$, most tests are concentrated in a range from 8.7 to 11.4 MPa (64% of the available data). It should be highlighted that the tensile strength reported by the researchers for tests collected in the database was obtained by a direct tensile test [61, 64, 69, 74, 75], splitting test [70, 71, 73, 76, 78], and notched beam flexural test [72]. This difference in testing methodology could affect the prediction of the structural response of UHPC-RC composite members. However, it is interesting that tested beams strengthened with UHPC overlay have a higher tensile strength value, demonstrating significant capacity improvement. The minimum compressive strength in Fig. 3 was close to 120 MPa, which is in good agreement with the minimum compressive strength requirement for UHPC [37]. Large f'_{UHPC} values appear to be associated with lower system effectiveness (i.e., lower V_{UHPC}/V_{Con} values), which also has been reported for strengthening with fibre-reinforced cementitious matrix (FRCM) [28]. The UHPC modulus of elasticity E_{UHPC} is distributed between 41 and 54 GPa. However, we cannot conclude a clear relationship between E_{UHPC} and shear capacity improvement for strengthened beams; that is, the gain in shear strength may not be proportional to E_{UHPC}.

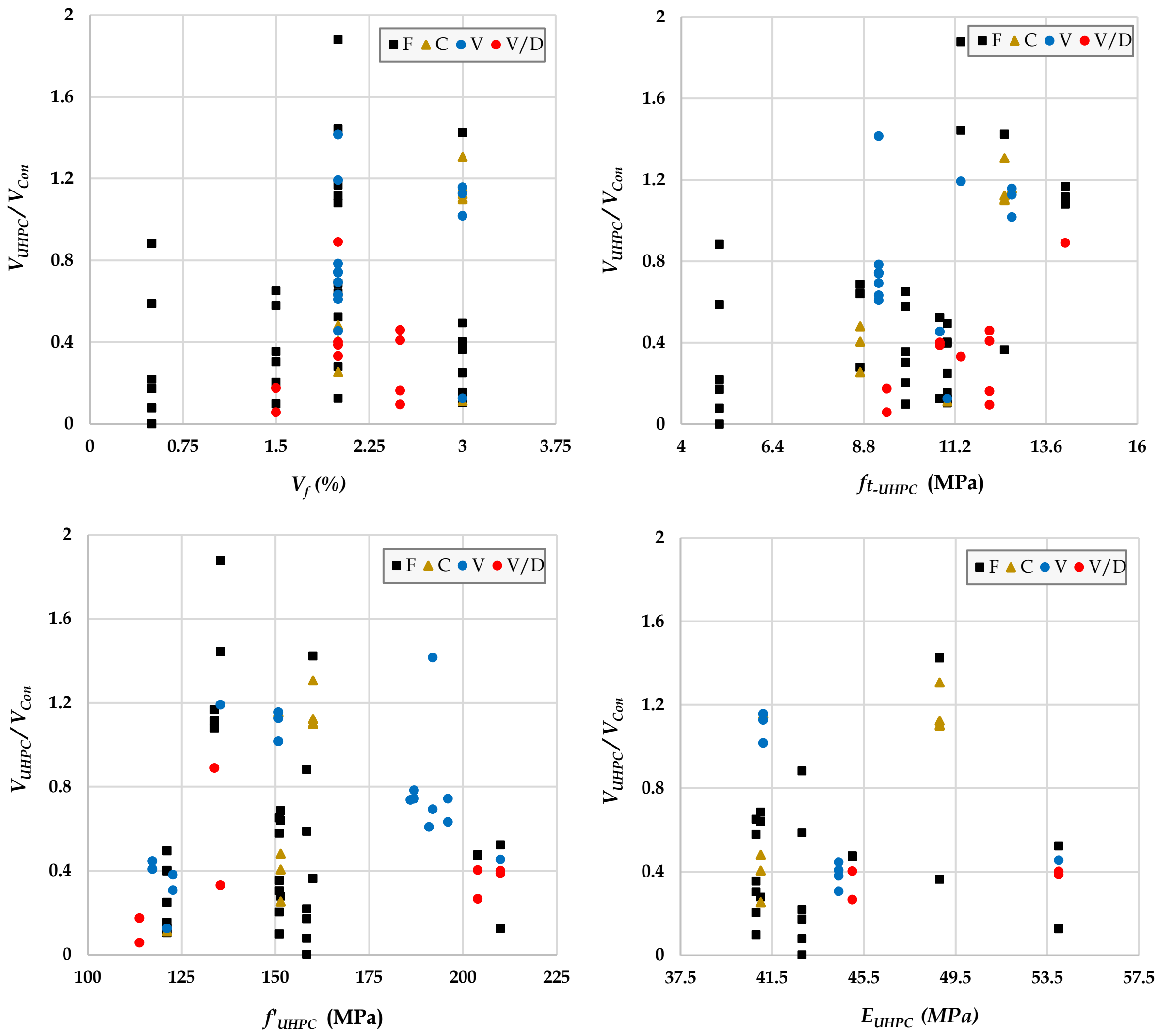


Fig. 3: Variation of V_{UHPC}/V_{Con} with V_f, $f_{t\text{-}UHPC}$, f'_{UHPC}, and E_{UHPC}.

2.1.3 Geometrical properties of the strengthening system

Fig. 4 presents the variation of V_{UHPC}/V_{Con} as a function of the strengthening system geometrical properties (thickness of UHPC layer (T_{UHPC}), strengthening configuration, bonding method and reinforcement in UHPC). Theoretically, the shear capacity of a strengthened beam will increase with increasing UHPC overlay thickness due to an increase in the concrete cross-section width. However, as shown in Fig. 4, increasing UHPC overlay thickness can help further improve the shear capacity of strengthened beams, but to a limited extent. According to Liu and Charron [64] increasing the thickness of UHPC lateral layers from 25 mm to 50 mm enhances the capacity by only 11 %. Other researchers found similar conclusions [71, 76, 77]. Regarding strengthening configuration, most of the tests have been conducted on beams strengthened with UHPC panels on both sides along the entire length of specimens (33%) or in the shear span region (25%), while UHPC strips have been used in only four tests. On the other hand, 14 % of the tests have been conducted on beams strengthened with U-shaped configurations. Comparing the additional shear strength V_{UHPC} relative to V_{Con} for these two configurations, although the 2S-continuous configuration has slightly higher values of V_{UHPC}/V_{Con}, it cannot be definitively concluded that using this configuration will guarantee a better performance of the beam strengthened with UHPC due to the flexural failure of all beams strengthened with U-shaped configuration. Also [61, 74, 76] concluded that U-wrapped configurations performed better than 2-sided bonded in terms of strength. Due to the benefits of UHPC's strain hardening behaviour under tension, the strengthening configuration of UHPC located at the tensile side was extensively evaluated for flexural strengthening [88]. However, this technique exhibits lower performance in shear strengthening when using unreinforced UHPC overlay. Section 2.3 presents further discussion on the most effective strengthening configuration.

The strengthening effect of different bonding methods (cast in-situ (CS), prefabricated laminates externally bonded with epoxy adhesion (EA) or anchorage with screw and bolt (AC), and casting of the UHPC with mechanical anchors (CS+AC)) is also analysed and compared in Fig. 4. It's found that 57% of the tests were performed on beams strengthening with casting UHPC in situ. In fact, if the interface strength is sufficient to withstand debonding until failure, the interface formed using various techniques should not significantly impact the shear capacity of the strengthened beam. It can be observed that casting UHPC in situ with anchors prevents this type of failure. However, in the other bonding methods, UHPC detachment was observed in some tests. As a result, answers must be provided on how to characterise interface performance and evaluate its influence on the shear capacity. In [63], the specimens anchored with UHPC failed after showing at least 15% more displacement than the epoxy-bonded ones. On the other hand, they state that when the bonding area increased (i.e., UHPC is applied as a continuous laminate), it may not be possible to provide a perfect bond between the beam and strengthening layer at every point; a better bond is achieved when UHPC is applied as strips. However, this finding differs from [78], who showed a slightly lower contribution when using UHPC strips vs. a continuous layer; also, it was accompanied by debonding failure.

Regarding using the UHPC layer combined with different types of reinforcement, 26% of the tests were carried out on beams strengthened with a reinforced UHPC layer. Although some higher values of V_{UHPC}/V_{Con} can be related to using transverse reinforcement combined with UHPC, it is not possible from Fig. 4 to determine the effectiveness of this technique in improving the shear resistance of the strengthened beams. Therefore, further discussion is presented in the next section.

2.2 Reinforcement in UHPC

In the UHPC layer, closely spaced reinforcing bars provide in-plane continuity, ensuring the layer's composite action with the RC element [89]. It has been found that the shear resistance of strengthened beams can be increased by reinforcing a UHPC overlay with steel bars (R-UHPC) [69, 73, 75], FRP bars (FRP-UHPC) [78] or using prestressing rods to produce a post-tensioned UHPC panel (P-UHPC) [72]. Fig. 5 illustrates the shear enhancement ratios due to different types of reinforcement in UHPC. According to Ji and Liu [75], additional 3Ø20 longitudinal rebars in a UHPC overlay in a tension side configuration for simply supported beams increased the shear resistance by about 31% compared to unreinforced UHPC. This enhancement is slightly higher than the 22% reported in [90] for a one-way simply supported slab with a similar thickness of R-UHPC. However, [69] found that using 4Ø8 longitudinal rebars in a UHPC overlay in a tension side configuration for cantilever beams resulted in a significant increase in shear resistance, ranging from 74% to 106% compared to RC beams strengthened with unreinforced UHPC. This indicates that the strengthening effect of steel-reinforced UHPC was notably pronounced in cantilever beams, while its impact on simply supported beams was less significant. This can be attributed to the R-UHPC layer, which resists shear by bending out-of-plane in double curvature, like the dowel action of rebar. In fact, for tension side strengthening configuration, [91] state that the contribution of the UHPC layer to the shear or punching shear resistance depends on the concrete's cracking state and the length of the cracking zone below the interface between the RC section and the UHPC layer. Further discussion on this phenomenon for tension side strengthening configuration is presented in Section 2.4. By strengthening with the post-tensioned UHPC panel from one side, the shear capacity can be enhanced by only 11% compared to the RC beam strengthened with a non-prestressed UHPC panel [72]. As shown in Fig. 5, the sided configuration utilized by [73], which reinforces UHPC with longitudinal and transverse steel bars, significantly increases the shear resistance of strengthened beams. Recently, instead of using transverse steel bars and like fabric-reinforced cementitious matrix (FRCM) strengthening systems, Nadir et al. [78] proposed UHPC combined with FRP composites for 2-sided shear strengthening of reinforced concrete beams. Both GFRP and CFRP bars were used in their study as inclined transverse reinforcement for reinforcing the UHPC layer. However, due to the flexural failure, which dominated the failure mode of beams strengthened with unreinforced UHPC, the addition of FRP bars showed a marginal increase in the shear capacity of strengthened beams. A similar new FRP-UHPC system using CFRP laminate [92], GFRP bars [58], and CFRP bars [59] was also investigated for the flexural strengthening of RC beams.

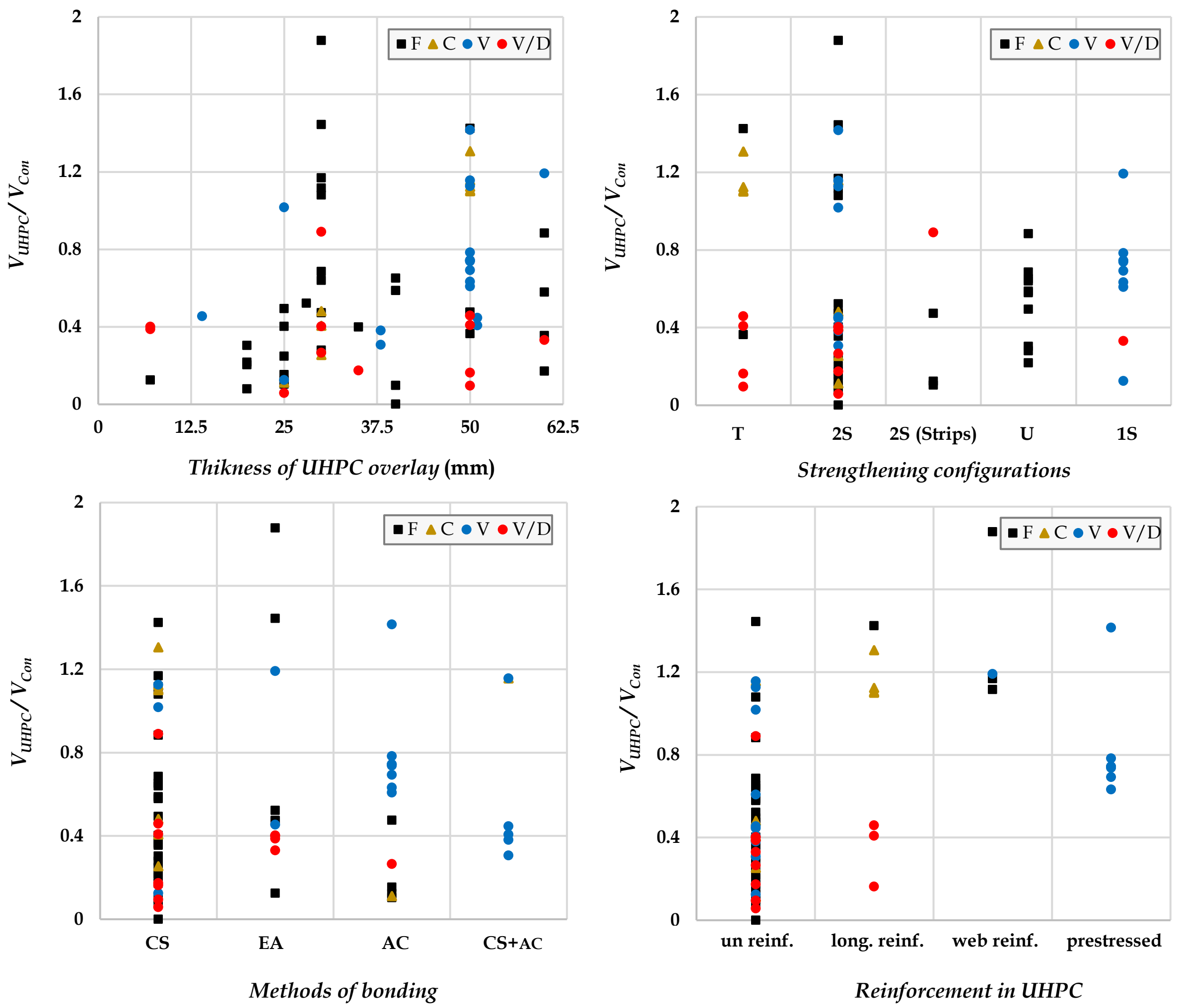


Fig. 4: Variation of V_{UHPC}/V_{Con} with Thickness of UHPC, Strengthening configuration, Method of bonding, and Reinforcement in UHPC.

[59] found that reducing the thickness of the UHPC overlay by reinforcing it with CFRP rebar could achieve a more sustainable, strong, and durable retrofitting system. Localised cracks can be avoided, and both the load capacity and ductility can be improved. However, evaluating the increase in shear resistance when the failure type changes is complex. Therefore, the effect of reinforcing UHPC for strengthening RC beams needs to be further studied.

2.3 Effectiveness of strengthening configuration with UHPC

Fig. 6 illustrates the observed contribution of Ultra-High-Performance Concrete (UHPC) to the measured shear strength, plotted against the total area of the UHPC overlay, based on the test data collected from the literature. The data points are distinctly categorized according to their strengthening configuration.

A significant observation from Fig. 6 is the exceptional effectiveness of strengthening reinforced concrete (RC) beams with UHPC overlays applied from two sides. This configuration demonstrated a remarkably high increase in shear strength compared to other strengthening approaches, even with a comparatively smaller amount of UHPC material.

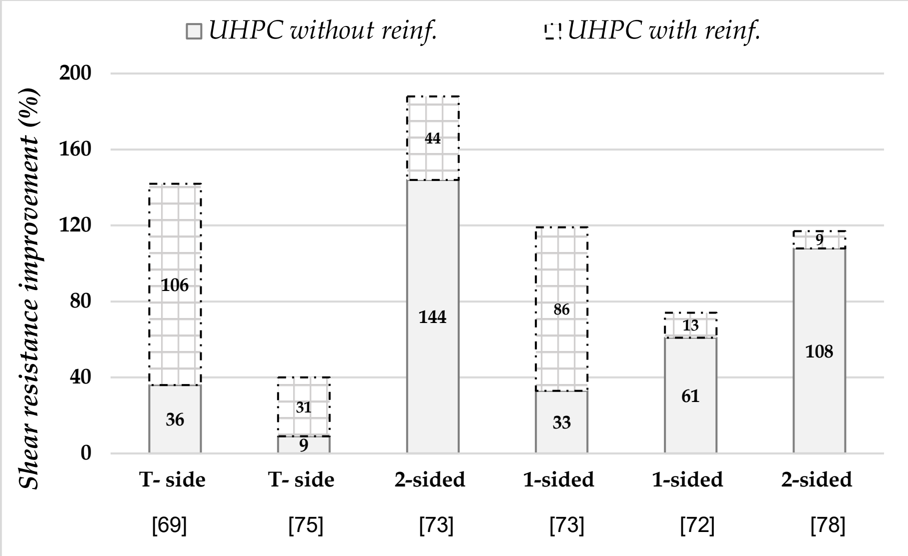


Fig. 5: Percentage of shear resistance improvement due to the addition of reinforcement in UHPC layer.

This finding suggests that merely increasing the total area of UHPC does not necessarily translate to a proportional increase in strengthening efficacy. In fact, the data appears to indicate a diminishing return, where an excessive increase in UHPC area in specific configurations might reduce the overall effectiveness of the UHPC overlay system. This unexpected behaviour could be attributed to a shift in the failure mode or issues related to composite action and stress distribution in larger overlay areas.

Regarding the U-shaped strengthening configuration, it is noteworthy that all beams employing this method primarily failed in flexure. Consequently, their contribution to enhancing shear capacity was not distinctly apparent in these tests, as the flexural failure mode governed the ultimate load. This highlights a crucial aspect: the effectiveness of a strengthening technique for a specific load type (e.g., shear) can be masked if another failure mode becomes dominant.

Conversely, the application of a reinforced-UHPC overlay on the tensile side, traditionally considered for flexural strengthening, also demonstrated an improvement in shear resistance. This outcome is particularly significant because flexural strengthening of existing RC beams often necessitates a concurrent increase in shear capacity to prevent premature shear failure, which can substantially escalate intervention costs. Therefore, employing a reinforced UHPC layer on the tensile side presents a promising and potentially cost-effective dual-purpose solution for retrofitting RC members. However, a critical question arises: can a reinforced UHPC layer on the tension side reliably contribute to a member's shear resistance and consistently obviate the need for dedicated shear strengthening? Addressing this requires further in-depth research. The current literature offers limited studies (only two references were identified in this database) that specifically investigate this technique for shear strengthening of RC beams.

Moreover, it is crucial to acknowledge that in those experimental works, the UHPC layers were reportedly extended beyond the supports. This boundary condition could significantly influence the measured shear performance by potentially providing additional anchorage, thus impacting the generalizability of their findings. The implications of this extension will be further elaborated in the subsequent section.

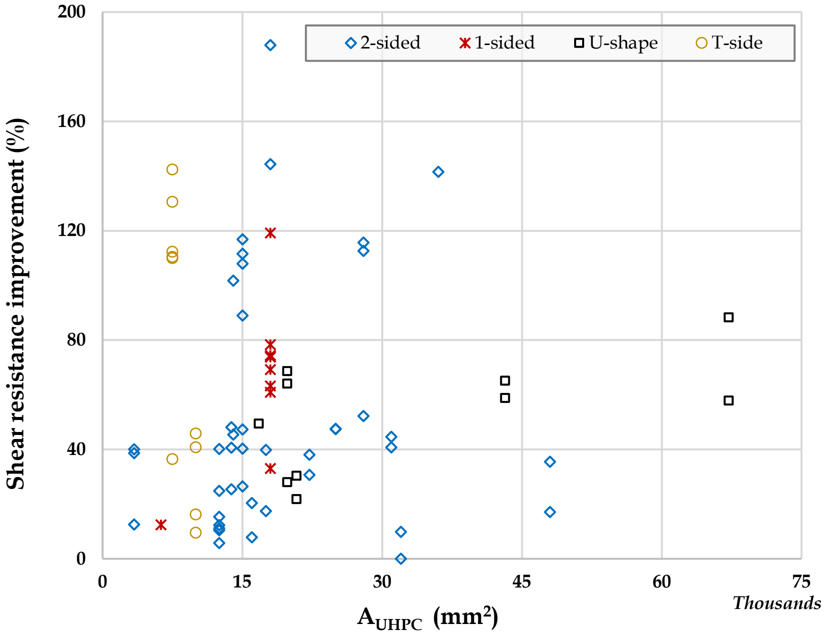


Fig. 6: UHPC's contribution to the shear strength as a function of its area.

2.4 Failure modes of UHPC strengthened beams

In this study, ambiguities were encountered in diagnosing failure modes for strengthened beams reported in certain references. In [73], the researchers categorized the type of failure using the terms brittle and ductile. In this review, brittle failure was interpreted as shear failure, and ductile failure as flexural failure. In [61], the researchers did not clearly mention the type of failure for some specimens; consequently, failure modes were determined based on rebar strain data and design criteria. Despite this, some references reported shear failure; however, observation of their load-deflection curves revealed a significant increase in deflection prior to failure, with the load becoming almost constant. This behaviour suggests a closer resemblance to flexural failure. However, for the purpose of this article, their reported failure modes were retained.

Regarding tension side configuration, [69] found that for cantilever beams strengthened with reinforced UHPC, prying stress on the UHPC layer at the combined flexural-shear crack mouth initiated intermediate-crack-induced debonding (ICD) between the UHPC layer and the RC beam prior to the maximum resistance. This phenomenon is attributed to the geometrical compatibility between the two elements, especially under high shear stress conditions. When subjected to combined bending and shear stress, one of the failure modes of UHPC-NC composite beams is the formation of an intermediate-crack-induced debonding (ICD) zone. This zone manifests as multiple flexural cracks that progressively degrade the interface area, leading to a decrease in the composite beam's stiffness and the creation of two hinges in the UHPC layer, as shown in Fig. 7.

As for simply supported concrete beams, only one hinge may be formed in the UHPC layer, and this is not observed in all cases. [75] justified this by explaining that the deformation curve of a simply supported beam is generally parabolic, with only one major crack traversing the entire depth of the beam. However, this type of failure was not observed for the experimental evidence on simply supported one-way slabs strengthened on the tension side with reinforced UHPC, which tend to fail by debonding between the UHPC and NSC composite interface, as indicated in [93].

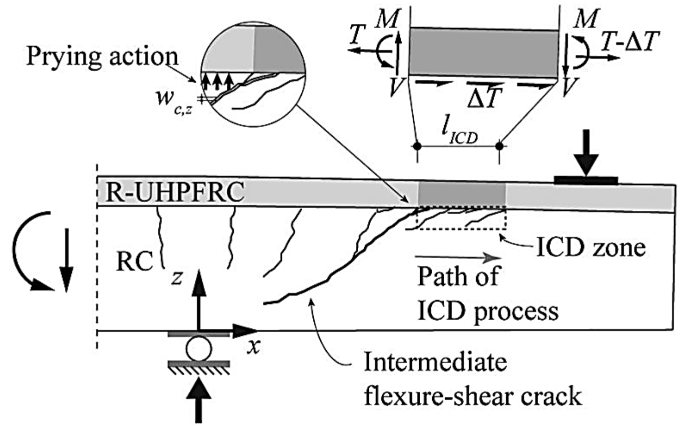
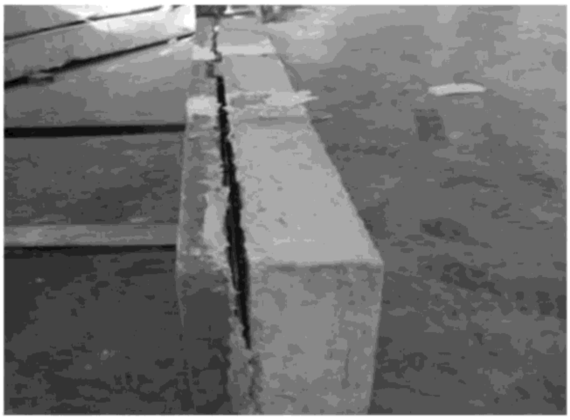


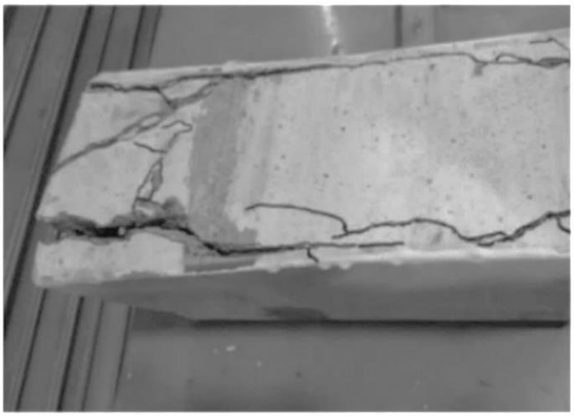
Fig. 7: Intermediate-crack-induced debonding (ICD), adapted from (Noshiravani & Brühwiler, 2014) [94].

All beams strengthened with U-jacket configurations have failed in a flexural failure mode. This form of failure agrees with the experimental data for U-wrapped beams with high-performance fibre-reinforced cementitious composites (HPFRCCs), which tend to fail in flexure [95]. However, one cannot conclude that this failure mode is exclusively related to this type of configuration, as changing the failure mode from shear to flexural failure could be attributed to the small difference between the shear and flexural design capacities of control beams. On the other hand, [61] reported that for some beams strengthened with U-shaped UHPC, after concrete crushing without longitudinal tensile steel bars yielding (flexural failure) and with continued loading, a diagonal crack appeared in the UHPC layer. It is essential to mention that, for both tension side and U-shaped configurations in previous studies, the UHPC layers were cast along the entire length of the tensile side, extending to the beam supports, which may not be feasible in practice for strengthening applications. In their experimental study for strengthening RC beams in flexure, [58] found that concrete cover separation failure occurs when the UHPC layer does not extend beyond the support. However, the literature does not report information on the overlap length and its design.

Identifying a typical failure mode for sided strengthening systems is not as straightforward as for tension side configurations. However, UHPC detachment, defined in this paper as the separation of the UHPC layer from the substrate (with or without concrete attached), is reported for specimens that were strengthened in this manner in some of the references [61, 63, 70, 71, 73, 76]. In five tests, debonding occurred between the UHPC and NSC composite interface without affecting the concrete surface, as shown in Fig. 8a. This could be attributed to poor surface preparation of the concrete substrate (low roughness) and/or inefficient use of the adhesive epoxy. Conversely, separation of the concrete cover (i.e., within the substrate), as shown in Fig. 8b, was also observed [63, 70, 71]. This could be caused by the elevated tensile force on the low-strength concrete used in the strengthened beams. On the other hand, anchorage rupture is another form of detachment that was reported in two specimens in which the UHPC layer was anchored to the RC beams with screws and bolts [63, 76]. However, it is not possible to conclude that the dominant mode of failure of UHPC strengthening system is associated with debonding of the UHPC layer, as other failure modes without debonding have also been reported in the available literature. As shown in Table 1, it is interesting that the reported failure mode for most of the sided strengthening configurations was unrelated to debonding of the UHPC layer from the substrate. This differs from beams strengthened with FRP composites, where two- or three-sided strengthening configurations fail mostly due to composite debonding [96]. In fact, to prevent the system from premature debonding, some codes for designing externally bonded FRP composites do not permit the side strengthening configurations to be used for strengthening RC beams in shear [97]. Considering that all control beams are designed for shear failure, it is also interesting to note that the capability to convert shear failure to flexural failure is not restricted to U-wrapped beams alone, as it has been observed in side-strengthened beams.



(a) UHPC debonding at the interface [73].



(b) Concrete cover separation failure [71].

Fig. 8: Detachment of UHPC layer.

3 Shear repairing of RC beams with UHPC

UHPC is an excellent material for repairing RC members due to its high strength and durability; it is used for repairing many types of concrete structures, such as bridges, piles and tunnels [55, 98, 99]. However, it may not be the most cost-effective solution in all cases [50]. Unlike the strengthening technology explained in Section 2, repairing RC beams with UHPC involves substituting a specific amount of concrete in the beams with UHPC, resulting in no changes to the cross-sectional area (see Fig. 9). Before applying the UHPC layer, the surface of the RC member needs to be prepared by removing any loose concrete, cleaning it thoroughly, and roughening it to ensure good adhesion; subsequently, the UHPC layer is typically applied using shotcrete or casting methods [55]. Reinforcement can also be added to the UHPC layer to provide additional strength. In most cases, the thickness of the UHPC layer depends on the concrete cover of the existing RC members.

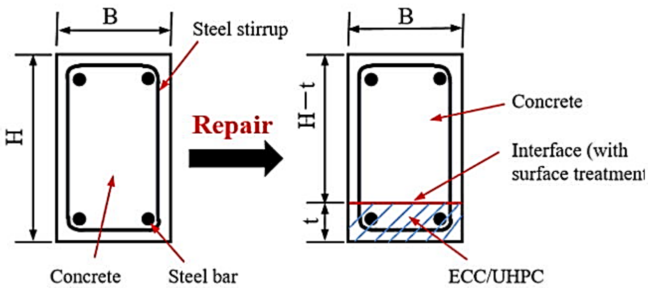


Fig. 9: UHPC layer for repairing RC beams[100].

To the best of the researcher's knowledge, two articles were found in the literature dealing with repairing RC beams with UHPC. In both studies, repair was performed by replacing the concrete cover in the shear span with cast-in-situ U-shaped jacketing of UHPC. In contrast to previous strengthening tests, Garg et al. [65] applied a UHPC layer to repair short RC beams, which were initially loaded up to 60% of the ultimate failure load of the reference beam. After the cracked concrete cover was removed, over-reinforced and under-reinforced beams were retrofitted with cast-in-situ U-shaped jacketing of UHPC in the shear span. Epoxy adhesive was also applied between the two layers. Over-reinforced and under-reinforced U-jacketed beams showed increases in load-carrying capability of 24.4% and 28.4%, respectively. Furthermore, fibres were effective in delaying crack propagation. However, the full effectiveness of the UHPC layer was not reached due to debonding between UHPC and the concrete substrate.

Like fabric-reinforced cementitious matrix (FRCM) strengthening systems, Chen et al. [62] proposed UHPC combined with FRP composites for the shear repair of corroded reinforced concrete beams. The UHPC-FRP grid composites, as shown in Fig. 10, were used to replace the spalled concrete cover on corroded RC beams. They found that using UHPC has proven effective in managing crack width and preventing internal steel stirrups from being invaded by environmentally corrosive substances, whereas the carbon FRP (CFRP) meshes in the UHPC layer increased their tensile strength. The UHPC-FRP composites significantly increased the shear capacity of the RC beams. The good bonding between the UHPC jacket and the CFRP grid led to excellent composite action and decreased the crack width in the concrete. Load-carrying capacity enhancements of 215% and 271% were observed for UHPC and UHPC-FRP grid U-jacketed beams, respectively. However, adding more FRP grid layers at the same corrosion level slightly reduced their shear contribution.

It is evident that the UHPC contribution in the experimental study of Chen et al. [62] exceeds the test data collected in the strengthening database significantly. This could be due to the cementitious material in their study, which had an ultimate tensile strain of 5.5%, significantly exceeding UHPC's typical range (0.1–0.8%) [100]. Additionally, the combination of UHPC with FRP showed a significant improvement in shear strength. Thus, one interesting finding of this review is that the effectiveness of UHPC overlay repair techniques is significantly increased by reinforcing the UHPC layer with FRP, which in turn enhances its tensile characteristics. However, the research on combining UHPC with FRP products for shear strengthening and repair of RC beams is limited, highlighting a potential area for new insights into this technology in the future.

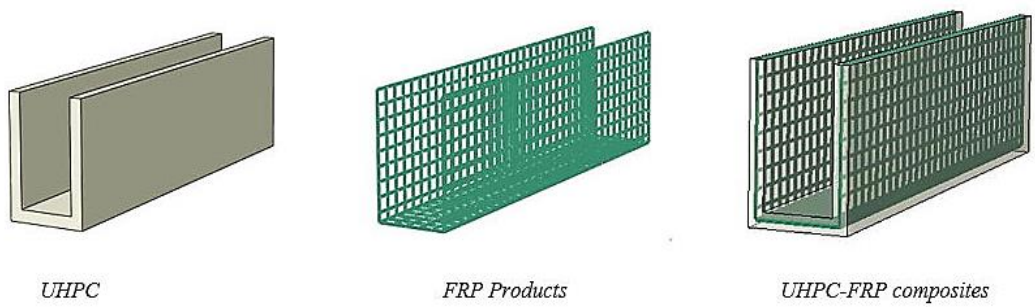


Fig. 10: The formation of UHPC-FRP composites.

5 Conclusions

This comprehensive review and compilation of an experimental database on RC beams strengthened with UHPC overlays provides a synthesized understanding of this promising technique. The analysis conclusively demonstrates that UHPC layers offer a highly effective solution for substantially enhancing the shear capacity of reinforced concrete beams, often modifying their failure modes from brittle shear to more ductile flexural behaviour.

The effectiveness of UHPC shear strengthening is governed by a complex interplay of parameters, including the shear span-to-effective depth ratio, the compressive strength of the concrete substrate, and the specific UHPC configuration and reinforcement. The study highlights that lower substrate concrete strengths can lead to undesirable cover separation, while further studies are needed on the effect of a/d ratios on the effectiveness of UHPC overlay. Furthermore, a critical insight revealed is the potential interaction between the UHPC overlay and internal transverse steel reinforcement, which may influence the full mobilization of the stirrups' contribution. On the other hand, strengthening RC beams by UHPC overlay from two sides was highly effective in increasing the shear strength compared to other forms of strengthening configuration, even with a lower amount of UHPC.

Various failure modes, such as intermediate-crack-induced debonding (ICD) under combined loading for beams strengthened on the tension side, detachment of the lateral UHPC layer, and fibre fracture within the shear cracks, underscore the importance of proper design and bonding techniques. Solutions like casting UHPC in situ with anchors are shown to be effective in mitigating debonding failures.

Beyond strengthening, the review reaffirms the significant potential of UHPC in repairing damaged RC beams. Integrating reinforcement, such as FRP, within the UHPC layer notably boosts the tensile characteristics and overall efficacy of repair techniques.

Despite these advancements, several critical areas warrant further investigation to fully unlock the potential of UHPC in structural applications. Future research should prioritize comprehensive experimental data collection on parameters currently lacking sufficient information, such as the precise strains in internal transverse shear reinforcement and the influence of the UHPC reinforcement ratio, including different fibre types. The role of anchors in preventing debonding also merits deeper study. Importantly, most prior investigations have focused on undamaged beams under static loading. Therefore, crucial research gaps exist in evaluating the shear performance of damaged RC beams retrofitted with UHPC and in understanding their response to cyclic loading, encompassing fatigue and seismic forces. Finally, further in-depth research is required to strengthen RC beams with tension-side reinforced UHPC overlay. Addressing these areas is essential for broad real-world applicability and robust design guidelines.

Appendix A

The geometrical and mechanical properties of the UHPC strengthened beams included in the experimental database are presented in Table A1.

Table A1
Experimental database.

Ref.	Specimen ID	Shape	RC Beam							UHPC			Strengthening with UHPC overlay				Results		
			b_w (mm)	d (mm)	a/d	f_c (MPa)	ρ_s	ρ_w	f_{vt} (MPa)	Vf (%)	f_{UHPC} (MPa)	$f_{t\text{-}UHPC}$ (MPa)	Config.	Reinforcement	Bond	Thickness (mm)	V_{UHPC} (MPa)	V_{UHPC}/V_{Con}	Failure mode
[69]	MW1	R	150	237	3.37	41.6	0.007	0.0017	516	3	160	10.2	T	-	CS	50	15.7	0.363	F
	MW2	R	150	237	3.37	41.6	0.007	0.0017	516	3	160	10.2	T	4Ø8 (long.)	CS	50	61.5	1.424	F
	MW3	R	150	237	3.37	41.6	0.007	0.0017	516	3	160	10.2	T	3Ø8 (long.)	CS	50	48.5	1.123	C
	MW4	R	150	237	3.37	41.6	0.007	0.0017	516	3	160	10.2	T	4Ø8 (long.)	CS	50	47.5	1.100	C
	MW5	R	150	237	3.37	41.6	0.007	0.0017	516	3	160	10.2	T	4Ø8 (long.)	CS	50	56.4	1.306	C
	MW6	R	150	237	3.37	41.6	0.013	0.0009	626	3	160	10.2	T	4Ø8 (long.)	CS	50	47.7	1.104	C
[70]	U2.5	R	150	200	2.5	19	0.020	0.0013	324	2	210	10.8	2S	-	EA	7	8.0	0.125	F
	U1.5	R	150	200	1.5	19	0.020	0.0013	415	2	210	10.8	2S	-	EA	7	36.5	0.386	D - V
[71]	1.5RDA	R	150	200	1.5	24.6	0.020	0.0013	548	2	210	10.8	2S	-	EA	7	34.7	0.400	D - V
	1.5RD14A	R	150	440	1.5	24	0.037	0.0051	333	2	210	10.8	2S	-	EA.	14	173.1	0.454	V
	1.5RD28A	R	150	440	1.5	24	0.037	0.0051	333	2	210	10.8	2S	-	EA.	28	199.2	0.522	F
[72]	DU9-2	R	250	320	2.5	40.6	0.030	0.0029	374	2	192	9.19	2S	Prestressing with 2.3 Mpa	SB.	50	424.5	1.415	V
	U9-2	R	250	320	2.5	45.5	0.030	0.0029	374	2	196	9.19	1S	Prestressing with 2.1 Mpa	SB.	50	189.6	0.632	V
	U11-2	R	250	320	2.5	40.4	0.030	0.0029	374	2	187	9.19	1S	Prestressing with 2.2 Mpa	SB.	50	234.9	0.783	V
	U13-2	R	250	320	2.5	40.3	0.030	0.0029	374	2	192	9.19	1S	Prestressing with 2.2 Mpa	SB.	50	207.6	0.692	V
	U11-0	R	250	320	2.5	44.3	0.030	0.0029	374	2	191	9.19	1S	-	SB.	50	182.4	0.608	V
	U11-1	R	250	320	2.5	41.8	0.030	0.0029	374	2	187	9.19	1S	Prestressing with 1.1 Mpa	SB.	50	222.9	0.743	V
	U11-3	R	250	320	2.5	50.5	0.030	0.0029	374	2	196	9.19	1S	Prestressing with 3 Mpa	SB.	50	222.9	0.743	V
	U13-4	R	250	320	2.5	40.9	0.030	0.0029	374	2	186	9.19	1S	Prestressing with 4.4 Mpa	SB.	50	221.1	0.737	V
[73]	ST-2S	R	150	258	2	30	0.013	0.0013	406	2	135.37	11.36	2S	-	EA.	30	83.0	1.443	F
	ST-1S	R	150	258	2	30	0.013	0.0013	406	2	135.37	11.36	1S	-	EA.	60	19.0	0.330	D - V
	ST-2S-R	R	150	258	2	30	0.013	0.0013	406	2	135.37	11.36	2S	3Ø8 (long.), and Ø8 @ 140 mm (stirrups)	EA.	30	108.0	1.878	F
	ST-1S-R	R	150	258	2	30	0.013	0.0013	406	2	135.37	11.36	1S	3Ø8 (long.), and Ø8 @ 140 mm (stirrups)	EA.	60	68.5	1.191	V
[74]	SB-2SJ-1.0	R	140	192	1	65	0.023	0.0060	610	2	151.4	8.7	2S	-	CS.	30	92.0	0.480	C
	SB-3SJ-1.0	R	140	192	1	65	0.023	0.0060	610	2	151.4	8.7	U	-	CS.	30	122.5	0.640	F
	SB-2SJ-1.5	R	140	192	1.5	65	0.023	0.0060	610	2	151.4	8.7	2S	-	CS.	30	58.0	0.406	C
	SB-3SJ-1.5	R	140	192	1.5	65	0.023	0.0060	610	2	151.4	8.7	U	-	CS.	30	98.0	0.685	F
	SB-2SJ-2.0	R	140	192	2	65	0.023	0.0060	610	2	151.4	8.7	2S	-	CS.	30	35.0	0.254	C
	SB-3SJ-2.0	R	140	192	2	65	0.023	0.0060	610	2	151.4	8.7	U	-	CS.	30	38.5	0.279	F
[75]	RC-U-2.7	R	200	443	2.7	46.2	0.028	0.0020	443	2.5	NR	8.78	T	-	CS.	50	31.0	0.095	V
	RC-RU-2.7	R	200	443	2.7	46.2	0.038	0.0020	443	2.5	NR	8.78	T	3Ø20 (long.)	CS	50	133.5	0.408	V
	RC-RU-2.4	R	200	443	2.26	46.2	0.038	0.0020	443	2.5	NR	8.78	T	3Ø20 (long.)	CS	50	150.0	0.458	V
	RC-RU-3.1	R	200	443	3.36	46.2	0.038	0.0020	443	2.5	NR	8.78	T	3Ø20 (long.)	CS	50	53.0	0.162	V

Table A1 (continued)

Ref.	Specimen ID	Shape	RC Beam							UHPC			Strengthening with UHPC overlay				Results		
			b_w (mm)	d (mm)	a/d	f_c (MPa)	ρ_s	ρ_w	f_{vt} (MPa)	Vf (%)	f_{UHPC} (MPa)	$f_{t\text{-}UHPC}$ (MPa)	Config.	Reinforcement	Bond	Thickness (mm)	V_{UHPC} (MPa)	V_{UHPC}/ V_{Con}	Failure mode
[63]	BEAM-2	R	150	220	4.55	20.2	0.023	0.0019	450	NR	204	NR	2S	-	EA.	30	17.0	0.402	D-V
	BEAM-3	R	150	220	4.55	20.1	0.023	0.0019	450	NR	204	NR	2S	-	SB.	30	11.2	0.265	D-V
	BEAM-4	R	150	220	4.55	20.4	0.023	0.0019	450	NR	204	NR	2S	-	EA.	50	20.1	0.473	F
	BEAM-5	R	150	220	4.55	20.5	0.023	0.0019	450	NR	204	NR	2S	-	SB.	50	20.1	0.475	F
	BEAM-6	R	150	220	4.55	20.3	0.023	0.0019	450	NR	204	NR	2S / Strips	-	EA.	30	20.0	0.473	F
[76]	B1	R	120	218	2.3	28	0.013	0.0024	293	1.5	113.7	9.4	2S	-	CS.	25	3.8	0.057	D-V
	B2	R	120	218	2.3	28	0.013	0.0024	293	1.5	113.7	9.4	2S	-	CS.	35	11.6	0.174	D-V
	B3	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	2S	-	CS.	25	26.8	0.401	F
	B4	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	2S	-	CS.	35	26.6	0.398	F
	B5	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	1S	-	CS.	25	8.3	0.124	V
	B6	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	U	-	CS.	25	33.0	0.494	F
	B7	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	2S	-	CS.	25	16.6	0.248	F
	B8	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	2S	-	SB.	25	10.2	0.153	F
	B9	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	2S	-	SB.	25	7.5	0.111	D-C
	B10	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	2S / Strips	-	SB.	25	6.9	0.104	F
	B11	R	120	218	2.3	28	0.013	0.0024	293	3	121.1	11	2S / Strips	-	SB.	25	8.2	0.123	F
[64]	TS-W50	T	250	320	3.125	29.8	0.053	0.0016	426.2	3	150.8	12.7	2S		CS	50	243.9	1.126	V
	TS-W25	T	250	320	3.125	29.8	0.053	0.0016	426.2	3	150.8	12.7	2S		CS	25	220.3	1.016	V
	TS-W50-A	T	250	320	3.125	29.8	0.053	0.0016	426.2	3	150.8	12.7	2S		CS+AC	50	250.5	1.156	C
[77]	Beam 1 - Test 1	I	101.6	406	2.25	37.2	0.047	0.0046	414	NR	117.2	NR	2S	-	CS+AC	51	98.5	0.407	V
	Beam 1 - Test 2	I	101.6	406	2.25	37.2	0.047	0.0046	414	NR	117.2	NR	2S	-	CS+AC	51	107.9	0.446	V
	Beam 2 - Test 1	I	101.6	406	2.25	37.2	0.047	0.0046	414	NR	122.7	NR	2S	-	CS+AC	38	74.1	0.306	V
	Beam 2 - Test 2	I	101.6	406	2.25	37.2	0.047	0.0046	414	NR	122.7	NR	2S	-	CS+AC	38	92.0	0.380	V
[61]	S1.5T2	R	200	349	3	36.3	0.028	0.0043	496.5	1.5	151.1	9.9	2S	-	CS.	20	51.4	0.203	F
	S1.5T4	R	200	349	3	36.3	0.028	0.0043	496.5	1.5	151.1	9.9	2S	-	CS.	40	24.7	0.098	F
	S1.5T6	R	200	349	3	36.3	0.028	0.0043	496.5	1.5	151.1	9.9	2S	-	CS.	60	89.6	0.354	F
	U1.5T2	R	200	349	3	36.3	0.028	0.0043	496.5	1.5	151.1	9.9	U	-	CS.	20	76.7	0.303	F
	U1.5T4	R	200	349	3	36.3	0.028	0.0043	496.5	1.5	151.1	9.9	U	-	CS.	40	164.8	0.651	F
	U1.5T6	R	200	349	3	36.3	0.028	0.0043	496.5	1.5	151.1	9.9	U	-	CS.	60	146.3	0.578	F
	S0.5T2	R	200	349	3	36.3	0.028	0.0043	496.5	0.5	158.4	5	2S	-	CS.	20	19.8	0.078	F
	S0.5T4	R	200	349	3	36.3	0.028	0.0043	496.5	0.5	158.4	5	2S	-	CS.	40	-6.1	0.000	D-F
	S0.5T6	R	200	349	3	36.3	0.028	0.0043	496.5	0.5	158.4	5	2S	-	CS.	60	43.3	0.171	D-F
	U0.5T2	R	200	349	3	36.3	0.028	0.0043	496.5	0.5	158.4	5	U	-	CS.	20	55.0	0.217	F
	U0.5T4	R	200	349	3	36.3	0.028	0.0043	496.5	0.5	158.4	5	U	-	CS.	40	148.6	0.587	F
	U0.5T6	R	200	349	3	36.3	0.028	0.0043	496.5	0.5	158.4	5	U	-	CS.	60	223.3	0.882	F

Table A1 (continued)

Ref.	Specimen ID	Shape	RC Beam							UHPC			Strengthening with UHPC overlay				Results		
			b_w (mm)	d (mm)	a/d	f'c (MPa)	ρ_s	ρ_w	f_{vt} (MPa)	Vf (%)	f_{UHPC} (MPa)	$f_{t\text{-}UHPC}$ (MPa)	Config.	Reinforcement	Bond	Thickness (mm)	V_{UHPC} (MPa)	V_{UHPC}/ V_{Con}	Failure mode
[78]	B30	R	150	222	2.7	36.6	0.015	0	-	2	133.8	14.1	2S	-	CS	30	59.25	1.079	F
	B30S	R	150	222	2.7	36.6	0.015	0	-	2	133.8	14.1	2S/STRIP	-	CS	30	48.85	0.889	D-V
	B30G	R	150	222	2.7	36.6	0.015	0	-	2	133.8	14.4	2S	Ø10 @ 100 inclined GFRP	CS	30	64.1	1.167	F
	B30C	R	150	222	2.7	36.6	0.015	0	-	2	133.8	14.4	2S	Ø10 @ 100 inclined GFRP	CS	30	64.1	1.167	F

Shape: R = Rectangular, T = T-beam, I = I- section. Configuration, see Table 1. Failure mode: F = Flexure, C= Combined, V = Shear, D = Detachment, see Table 1. NR = Not reported. Method of bond: CS = Cast in situ, EA = Epoxy adhesion, AC = Anchors, SB = Fixed with Screw and bolt. b and d are cross-section width and effective depth of unstrengthen beams, respectively. Vf, f'_{UHPC}, and $ft_{\text{-}UHPC}$, represent fibre content, the compressive strength, and tensile strength of UHPC, respectively.

References

[1] ASCE (2021): 2021 Report card for America's infrastructure. Reston.
[2] THERMOU, G. E. – PANTAZOPOULOU, S. J. – ELNASHAI, A. S. (2007): Flexural Behavior of Brittle RC Members Rehabilitated with Concrete Jacketing. Journal of Structural Engineering 133:1373–1384.
[3] ACI Committee 546 (2014) Guide to Concrete Repair (ACI 546-14). (ACI) American Concrete Institute, Farmington Hills, MI.
[4] HARAJLI, M. H. (1993): Strengthening of Concrete Beams by External Prestressing. PCI Journal 38:76–88.
[5] ADHIKARY, B. B. – MUTSUYOSHI, H. – SANO, M. (2000): Shear strengthening of reinforced concrete beams using steel plates bonded on beam web: experiments and analysis. Constr Build Mater 14:237–244.
[6] TAHSIRI, H. – SEDEHI, O. – KHALOO, A. – RAISI, E. M. (2015): Experimental study of RC jacketed and CFRP strengthened RC beams. Constr Build Mater 95:476–485.
[7] CHEONG, H. K. – MACALEVEY, N. (2000): Experimental Behavior of Jacketed Reinforced Concrete Beams. Journal of Structural Engineering 126:692–699.
[8] NARAYAN SWAMY, R. – ABDELHAMID CHARIF, R. J. (o. J.): Contribution of Externally Bonded Steel Plate Reinforcement to the Shear Resistance of Reinforced Concrete Beams. ACI Symposium Publication 165.
[9] JAYANANDA, N. (2018): Shear Strengthening of Prestressed Concrete Beams with Ultra-High Performance Fibre Reinforced Concrete: Numerical Analysis by ATENA Model. Delft University of Technology, Delft, Netherlands.
[10] SEZEN, H. (2012): Effectiveness of Repair and Strengthening Methods for Reinforced Concrete Columns and Beam-Column Joints. Structures Congress 2012, 2015–2024.
[11] QASSIM, H. J. – MASHREI, M. A. (2024): Flexural Strength of RC Continuous Beams Strengthened by CFRP Using EBR and EBROG Methods: Experimental and Analytical Study. Civil and Environmental Engineering 20:580–592.
[12] ADHIKARY, B. B. – MUTSUYOSHI, H. (2004): Behavior of Concrete Beams Strengthened in Shear with Carbon-Fiber Sheets. Journal of Composites for Construction 8:258–264.
[13] NORRIS, T. – SAADATMANESH, H. – EHSANI, M. R. (1997): Shear and Flexural Strengthening of R/C Beams with Carbon Fiber Sheets. Journal of Structural Engineering 123:903–911.
[14] CHAALLAL, O. – NOLLET, M. J. – PERRATON, D. (1998): Shear Strengthening of RC Beams by Externally Bonded Side CFRP Strips. Journal of Composites for Construction 2:111–113.
[15] BOUSSELHAM, A. – CHAALLAL, O. (2004): Shear strengthening reinforced concrete beams with fiber-reinforced polymer: Assessment of influencing parameters and required research. Structural Journal 101:219–227.
[16] KADHIM, M. M. A. – JAWDHARI, A. R. – ALTAEE, M. J. – ADHEEM, A. H. (2020): Finite element modelling and parametric analysis of FRP strengthened RC beams under impact load. Journal of Building Engineering 32:101526.
[17] CHAJES, M. J. – JANUSZKA, T. F. – MERTZ, D. R. – THOMSON, T. A. – FINCH, W. W. (1995): Shear Strengthening of Reinforced Concrete Beams Using Externally Applied Composite Fabrics. ACI Struct J 92:295–303.
[18] LIU, T. Q. – LIU, X. – FENG, P. (2020): A comprehensive review on mechanical properties of pultruded FRP composites subjected to long-term environmental effects. Compos B Eng 191:107958.
[19] DUO, Y. – LIU, X. – LIU, Y. – TAFSIROJJAMAN, T. – SABBROJJAMAN, M. (2021): Environmental impact on the durability of FRP reinforcing bars. Journal of Building Engineering 43:102909.
[20] AL-SALLOUM, Y. A. – ELSANADEDY, H. M. – ALSAYED, S. H. – IQBAL, R. A. (2012): Experimental and numerical study for the shear strengthening of reinforced concrete beams using textile-reinforced mortar. Journal of Composites for Construction 16:74–90.
[21] BURKE, P. J. – BISBY, L. A. – GREEN, M. F. (2013): Effects of elevated temperature on near surface mounted and externally bonded FRP strengthening systems for concrete. Cem Concr Compos 35:190–199.
[22] ABADEL, A. A. (2021): Experimental investigation for shear strengthening of reinforced self-compacting concrete beams using different strengthening schemes. Journal of Materials Research and Technology 15:1815–1829.
[23] OEHLERS, D. J. (2001): Development of design rules for retrofitting by adhesive bonding or bolting either FRP or steel plates to RC beams or slabs in bridges and buildings. Composites Part A-applied Science and Manufacturing 32:1345–1355.

[24] MOHAMMED, M. J. - AL-AZZAWI, A. A. (2024): Torsional Performance of Reinforced Concrete Beams Strengthened Using Hybrid Fibers Sifcon Jacketing. Civil and Environmental Engineering 20:684–698.

[25] ABD-AL-NASER, M. – HARBA, I. S. I. (2023) Strengthening of Reinforced Concrete Beams with Textile-Reinforced Concrete. Civil and Environmental Engineering 19:596–609.

[26] GANDEL, R. – JERABEK, J. – MARCALIKOVA, Z. (2023): Reinforced Concrete Beams Without Shear Reinforcement Using Fiber Reinforced Concrete and Alkali-Activated Material. Civil and Environmental Engineering 19:348–356.

[27] ACI Committee 549 (2020): Guide to Design and Construction of Externally Bonded Fabric-Reinforced and Steel-Reinforced Grout Systems for Repair and Strengthening of Concrete Structures. ACI 5494R-20. Farmington Hills MI, USA.

[28] GONZALEZ-LIBREROS, J. H. – SABAU, C. – SNEED, L. H. – PELLEGRINO, C. – SAS, G. (2017): State of research on shear strengthening of RC beams with FRCM composites. Constr Build Mater 149:444–458.

[29] WAKJIRA, T. G. – Ebead, U. (2019): A shear design model for RC beams strengthened with fabric reinforced cementitious matrix. Eng Struct 200:109698.

[30] TETTA, Z. C. – TRIANTAFILLOU, T. C. – BOURNAS, D. A. (2018): On the design of shear-strengthened RC members through the use of textile reinforced mortar overlays. Compos B Eng 147:178–196.

[31] OLUWAFUNMILAYO, A. – TAMER, E. M. – AHMED, E. R. (2016): Numerical Simulation and Experimental Testing of Concrete Beams Strengthened in Shear with Fabric-Reinforced Cementitious Matrix. Journal of Composites for Construction 20:04016056.

[32] LI, H. – XU, S., LEUNG, C. K. Y. (2009): Tensile and flexural properties of ultra high toughness cementious composite. Journal of Wuhan University of Technology-Mater Sci Ed 24:677–683.

[33] YU, K. – LI, L. – YU, J. – WANG, Y. – YE, J. – XU, Q. F. (2018): Direct tensile properties of engineered cementitious composites: A review. Constr Build Mater 165:346–362.

[34] LIU, H. – ZHANG, Q. – GU, C. – SU, H. – LI, V. (2017): Influence of microcrack self-healing behavior on the permeability of Engineered Cementitious Composites. Cem Concr Compos 82:14–22.

[35] LI, V. – WANG, S. X. – WU, C. (2001): Tensile strain-hardening behavior or polyvinyl alcohol engineered cementitious composite (PVA-ECC). ACI Mater J 98:483–492.

[36] AL-BAGHDADI, H. M. – KADHUM, M. M. (2025): Performance and Mechanical Properties of Environmentally Engineered Cementitious Composites Produced from Local Waste. Civil and Environmental Engineering 0.

[37] ASTM C1856 / C1856M-17 (2017): Standard practice for fabricating and testing specimens of ultra-high performance concrete. ASTM International, West Conshohocken, PA.

[38] JSCE (2006): Recommendations for design and construction of ultra-high strength fiber reinforced concrete structures (Draft). Japan Society of Civil Engineers Tokyo, Japan.

[39] EL-DIEB, A. S. (2009): Mechanical, durability and microstructural characteristics of ultra-high-strength self-compacting concrete incorporating steel fibers. Mater Des 30:4286–4292.

[40] HASSAN, A. M. T. – JONES, S. W. – MAHMUD, G. H. (2012): Experimental test methods to determine the uniaxial tensile and compressive behaviour of ultra high performance fibre reinforced concrete (UHPFRC). Constr Build Mater 37:874–882.

[41] ROSSI, P. (2013): Influence of fibre geometry and matrix maturity on the mechanical performance of ultra high-performance cement-based composites. Cem Concr Compos 37:246–248.

[42] GRAYBEAL, B. (2006): Material Property Characterization of Ultra-High Performance Concrete. FHWA-HRT-06-103 1–176.

[43] KANG, S. T., LEE, Y. – PARK, Y.-D. – KIM, J. K. (2010): Tensile fracture properties of an Ultra High Performance Fiber Reinforced Concrete (UHPFRC) with steel fiber. Compos Struct 92:61–71.

[44] LEE, M. G. – WANG, Y. C. – CHIU, C. T. (2007): A preliminary study of reactive powder concrete as a new repair material. Constr Build Mater 21:182–189.

[45] BEHLOUL, M. (2007): HPFRCC field of applications: Ductal® recent experience. Proceedings of the international RILEM workshop ‘High performance fiber reinforced cement composites’ HPFRCC5, Mainz, 213–222.

[46] BUITELAAR, P. (2004): Ultra High Performance Concrete: Developments and Applications during 25 years. Plenary Session International Symposium on UHPC September 13 - 15, 2004, Kassel, Germany.

[47] BERTOLA, N. – SCHILTZ, P. – DENARIÉ, E. – BRÜHWILER, E. (2021): A Review of the Use of UHPFRC in Bridge Rehabilitation and New Construction in Switzerland. Front Built Environ 7.

[48] WIBOWO, H. – SRITHARAN, S. (2018): Use of Ultra-High-Performance Concrete for Bridge Deck Overlays.
[49] MINELLI, F. – COMINOLI, L. – MEDA, A. – PLIZZARI, G. A. – RIVA, P. (2006): Full-scale tests on HPSFRC prestressed roof elements subjected to longitudinal flexure. RILEM-PRO 49 International RilemWorkshop on High Performance Fiber Reinforced Cementitious Composites (HPFRCC).
[50] BRÜHWILER, E. – DENARIÉ, E. (2008): Rehabilitation of concrete structures using Ultra-High Performance Fibre Reinforced Concrete. University of Kassel: Kassel.
[51] MANSOUR, W. – TAYEH, B. A. (2020): Shear Behaviour of RC Beams Strengthened by Various Ultrahigh Performance Fibre-Reinforced Concrete Systems. Advances in Civil Engineering 2020.
[52] OMBRES, L. (2015): Structural performances of reinforced concrete beams strengthened in shear with a cement based fiber composite material. Compos Struct 122:316–329.
[53] KADHIM, M. M. A. – SALEH, A. R. – CUNNINGHAM, L. S. – SEMENDARY, A. A. (2021): Numerical investigation of non-shear-reinforced UHPC hybrid flat slabs subject to punching shear. Eng Struct 241.
[54] KADHIM, M. M. A. – JAWDHARI, A. – PEIRIS, A. (2021): Development of hybrid UHPC-NC beams: A numerical study. Eng Struct 233.
[55] DOIRON, G. (2019): UHPC Shotcrete - A New Way to Install UHPC. International Interactive Symposium on Ultra-High Performance Concrete 2.
[56] HUANG, Y. – LEE, M. G. – KAN, Y. C. – WANG, W. C. – WANG, Y. C. – PAN, W. B. (2022): Reinforced concrete beams retrofitted with UHPC or CFRP. Case Studies in Construction Materials 17.
[57] MOOSA, M. K. – ALI, A. Y. (2023): Experimental Investigation on The Transform The Simply Supported Girders to Continuous Girder by Using The UHPC Cast in Place Joint. KSCE Journal of Civil Engineering 27:1697–1707.
[58] MIRDAN, D. – SALEH, A. R. (2022): Flexural performance of reinforced concrete (RC) beam strengthened by UHPC layer. Case Studies in Construction Materials 17.
[59] KADHIM, M. M. A. – JAWDHARI, A. – NADIR, W. – Cunningham, L. S. (2022): Behaviour of RC beams strengthened in flexure with hybrid CFRP-reinforced UHPC overlays. Eng Struct 262.
[60] HABER, Z. – FODEN, A. – McDONAGH, M. – OCEL, J. – ZMETRA, K. – GRAYBEAL, B. (2022): Design and Construction of UHPC-Based Bridge Preservation and Repair Solutions.
[61] HONG, S. G. – LIM, W. Y. (2023): Strengthening of shear-dominant reinforced concrete beams with ultra-high-performance concrete jacketing. Constr Build Mater 365.
[62] CHEN, C. – CAI, H. – CHENG, L. (2021): Shear Strengthening of Corroded RC Beams Using UHPC–FRP Composites. Journal of Bridge Engineering 26.
[63] TANARSLAN, H. M. – YALÇINKAYA, Ç. – ALVER, N. – KARADEMIR, C. (2021): Shear strengthening of RC beams with externally bonded UHPFRC laminates. Compos Struct 262.
[64] LIU, T. – CHARRON, J. P. (2022): Shear strengthening of concrete T-beams with lateral layers of UHPC. MATEC Web of Conferences 364:04016.
[65] GARG, V. – BANSAL, P. P. – SHARMA, R. (2019): Retrofitting of Shear-Deficient RC Beams Using UHP-FRC. Iranian Journal of Science and Technology - Transactions of Civil Engineering 43:419–428.
[66] AFGC (Association Francaise de Génie Civil) (2013): Ultra High Performance Fibre-Reinforced Concretes, Recommendations. AFGC Publication. Paris, France.
[67] Korea Concrete Institute (2012): Design Recommendations for Ultra-High Performance Concrete K-UHPC.
[68] WIROJJANAPIROM, P. – MATSUMOTO, K. – KONO, K. – NIWA, J. (2013): Experimental study on shear behavior of RC beams using U-shaped UFC permanent formwork with shear keys and bolts. Journal of Japan Society of Civil Engineers, Ser E2 (Materials and Concrete Structures) 69:67–81.
[69] NOSHIRAVANI, T. – BRÜHWILER, E. (2013): Experimental Investigation on Reinforced Ultra-High-Performance Fiber-Reinforced Concrete Composite Beams Subjected to Combined Bending and Shear. ACI Struct J 110.
[70] WANG, J. – MORIKAWA, H. – KAWAGUCHI, T. (2013): Influence of Strengthening by Ultra High Strength Fibre Reinforced Concrete Panels on Shear Resisting Mechanism and Bond-Slip Behavior of Low Strength RC Members. In: Kyoto Research Park (Hrsg) Third International Conference on Sustainable Construction Materials and Technologies. Japan.
[71] WANG, J. – MORIKAWA, H. – KAWAGUCHI, T. (2015): Shear strengthening of RC beams using ultra-high-strength fibre-reinforced concrete panels. Magazine of Concrete Research 67:718–729.

[72] LIMPANINLACHAT, P. – NAKAMURA, T. – KONO, K. – NIWA, J. (2017): Shear strengthening performance of post-tensioned UFC panel on reinforced concrete beams. Journal of Advanced Concrete Technology 15:558–573.

[73] SAKR, M. A. – SLEEMAH, A. A. – KHALIFA, T. M. – MANSOUR, W. N. (2019): Shear strengthening of reinforced concrete beams using prefabricated ultra-high performance fiber reinforced concrete plates: Experimental and numerical investigation. Structural Concrete 20:1137–1153.

[74] BAHRAQ, A. A. – AL-OSTA, M. A. – AHMAD, S. – AL-ZAHRANI, M. M. – AL-DULAIJAN, S. O. – RAHMAN, M. K. (2019): Experimental and Numerical Investigation of Shear Behavior of RC Beams Strengthened by Ultra-High Performance Concrete. Int J Concr Struct Mater 13.

[75] JI, H. – LIU, C. (2020): Ultimate shear resistance of ultra-high performance fiber reinforced concrete-normal strength concrete beam. Eng Struct 203.

[76] SAID, A. – ELSAYED, M. – EL-AZIM, A. A. – ALTHOEY, F. – TAYEH, B. A. (2022): Using ultra-high performance fiber reinforced concrete in improvement shear strength of reinforced concrete beams. Case Studies in Construction Materials 16.

[77] KODSY, A. M. (2022): Repair and strengthening of concrete bridges using ultra-high-performance concrete (UHPC). The University of Nebraska-Lincoln, Lincoln.

[78] NADIR, W. – KADHIMI, M. M. A. – JAWDHARI, A. – FAM, A. – MAJDI, A. (2023): RC beams strengthened in shear with FRP-Reinforced UHPC overlay: An experimental and numerical study. Structures 53:693–715.

[79] KANI, G. (1967): How safe are our large reinforced concrete beams? Journal Proceedings, Bd. 64 128–141.

[80] BAGGIO, D. – SOUDKI, K. – NOËL, M. (2014): Strengthening of shear critical RC beams with various FRP systems. Constr Build Mater 66:634–644.

[81] TZOURA, E.: Structures TT-M and, 2016 undefined (2016) Shear strengthening of reinforced concrete T-beams under cyclic loading with TRM or FRP jackets. Springer28–49:17

[82] ESCRIG, C. – GIL, L. – BERNAT-MASO, E. – PUIGVERT, F. (2015): Experimental and analytical study of reinforced concrete beams shear strengthened with different types of textile-reinforced mortar. Constr Build Mater 83:248–260.

[83] BLANKSVÄRD, T. – TÄLJSTEN, B. – CAROLIN, A. (2009): Shear strengthening of concrete structures with the use of mineral-based composites. Journal of Composites for Construction 13:25–34.

[84] PELLEGRINO, C. – VASIC, M. (2013): Assessment of design procedures for the use of externally bonded FRP composites in shear strengthening of reinforced concrete beams. Compos B Eng 45:727–741.

[85] CHEN, G. M. – TENG, J. G. – CHEN, J. F. – ROSENBOOM, O. A. (2010): Interaction between steel stirrups and shear-strengthening FRP strips in RC beams. Journal of Composites for Construction 14:498–509.

[86] PELLEGRINO, C. – MODENA, C. (2006): Fiber-reinforced polymer shear strengthening of reinforced concrete beams: Experimental study and analytical modeling. ACI Struct J 103:720.

[87] LANTSOGHT, E. O. L. (2019): How do steel fibers improve the shear capacity of reinforced concrete beams without stirrups? Compos B Eng 175:107079.

[88] ZHU, Y. – ZHANG, Y. – HUSSEIN, H. H. – CHEN, G. (2020): Flexural strengthening of reinforced concrete beams or slabs using ultra-high performance concrete (UHPC): A state of the art review. Eng Struct. Elsevier Ltd.

[89] HABEL, K. – DENARIÉ, E. – BRÜHWILER, E. (2006): Structural Response of Elements Combining Ultrahigh-Performance Fiber-Reinforced Concretes and Reinforced Concrete. Journal of Structural Engineering 132:1793–1800.

[90] YIN, H. – TEO, W. – SHIRAI, K. (2017): Experimental investigation on the behaviour of reinforced concrete slabs strengthened with ultra-high performance concrete. Constr Build Mater 155:463–474.

[91] BASTIEN-MASSE, M. – BRÜHWILER, E. (2016): Contribution of R-UHPFRC strengthening layers to the shear resistance of RC elements. Structural Engineering International 26:365–374.

[92] GENEDY, M. (2014): A New CFRP-UHPC System for Strengthening Reinforced Concrete T-Beams (thesis). University of New Mexico, USA, USA Abgerufen von https://digitalrepository.unm.edu/ce_etds/93.

[93] YIN, H. – TEO, W. – SHIRAI, K. (2017): Experimental investigation on the behaviour of reinforced concrete slabs strengthened with ultra-high performance concrete. Constr Build Mater 155:463–474.

[94] NOSHIRAVANI, T. – BRÜHWILER, E. (2014): Analytical Model for Predicting Response and Flexure-Shear Resistance of Composite Beams Combining Reinforced Ultrahigh Performance Fiber-Reinforced Concrete and Reinforced Concrete. Journal of Structural Engineering 140:04014012.
[95] MEDA, A. – RIVA SM, P. (2014): Shear Strengthening of Reinforced Concrete Beam with High-Performance Fiber-Reinforced Cementitious Composite Jacketing. ACI Struct J 111.
[96] KHALIFA, A. – GOLD, W. – NANNI, A. (1998): Contribution of Externally Bonded FRP to Shear Capacity of RC Flexural Members. Journal of Composites for Construction - J COMPOS CONSTR 2.
[97] National Research Council (CNR) (2013): Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures. Roma.
[98] SRITHARAN, S. – DOIRON, G. – BIERWAGEN, D. – KEIERLEBER, B. – ABU-HAWASH, A. (2018): First application of UHPC bridge deck overlay in North America. Transp Res Rec 2672:40–47.
[99] HABER, Z. B. – FODEN, A. – McDONAGH, M. – OCEL, J. M. – ZMETRA, K. – GRAYBEAL, B. A. (2022): Design and Construction of UHPC-Based Bridge Preservation and Repair Solutions. United States. Federal Highway Administration. Office of Infrastructure .
[100] PAN, B. – LIU, F – ZHUGE, Y. – ZENG, J. J. – LIAO, J. J. (2022): ECCs/UHPFRCCs with and without FRP reinforcement for structural strengthening/repairing: A state-of-the-art review. Constr Build Mater 316:125824.