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REVIEW

Review of Behavior Flexural Strengthened RC Beams Using Ultra-High Performance Concrete

Revisión del Comportamiento de Vigas de CR Reforzadas a Flexión Utilizando Hormigón de Altas Prestaciones

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ABSTRACT

The use of ultra-high performance concrete (UHPC) to reinforce existing reinforced concrete (RC) structures in flexure has made great strides in research recently. In addition to creating an experimental archive, the research provided a thorough technical literature review. The effectiveness of UHPC strengthening schemes for RC beams was assessed by examining the effect of size on the flexural strengthening performance of RC members with UHPC. Various dimensions of RC elements were considered in order to understand any possible size-related effects. Factors like material strength and stiffness of the current RC members were considered because they could affect the strengthening's overall effectiveness. To comprehend how the strengthening of the UHPC would impact the overall. In order to find the most successful strategy, various UHPC strengthening configurations were examined. prior to applying the UHPC, the concrete substrate must be prepared. The experimental results from the studies under review indicate that UHPC is a promising reinforcement that can successfully provide RC beams flexural strength. The plain overlay's bending capacity increased by 20 % to 60 % when the thickness of the UHPC overlay was increased within the range of 30 to 50 mm. In contrast to plain overlays, the reinforced overlay resulted in a notable 40 %-85 % increase in flexural capacity. To assist stakeholders in making decisions, a cost comparison of UHPC with other strengthening techniques, such as carbon fiber reinforced polymers (CFRP), was provided. The study concludes by highlighting the potential of UHPC as a workable option for flexural strengthening of existing RC structures and offers insightful information for furthering the advancement and application of this technology in the building sector.

Keywords: Concrete; Ultra-High Performance Concrete; Flexure; Overlay; Strengthening, Review.

RESUMEN

El uso de hormigón de ultra altas prestaciones (UHPC) para reforzar estructuras existentes de hormigón armado (RC) a flexión ha experimentado grandes avances en la investigación recientemente. Además de crear un archivo experimental, la investigación proporcionó una revisión exhaustiva de la literatura técnica. La eficacia de los esquemas de refuerzo con UHPC para vigas de CR se evaluó examinando el efecto del tamaño en el rendimiento del refuerzo a flexión de los elementos de CR con UHPC. Se consideraron varias dimensiones de los elementos de CR para comprender cualquier posible efecto relacionado con el tamaño. Factores como la resistencia del material y la rigidez de los elementos de CR actuales se tuvieron en cuenta porque podrían afectar a la eficacia global del refuerzo. Para comprender cómo el refuerzo del UHPC afectaría al conjunto. Antes de aplicar el UHPC, debe prepararse el sustrato de hormigón. Los resultados experimentales de los estudios analizados indican que el UHPC es un refuerzo prometedor que puede proporcionar con éxito resistencia a flexión a las vigas de CR. La capacidad de flexión del recubrimiento liso aumentó entre un 20 % y un 60 % cuando el espesor del recubrimiento de UHPC se incrementó entre 30 y 50 mm. En contraste con los recubrimientos lisos, el recubrimiento reforzado produjo un notable aumento del 40 % al 85 % en la capacidad de flexión. Para ayudar a los interesados en la toma de decisiones, se facilitó una comparación de costes del UHPC con otras técnicas de refuerzo, como los polímeros reforzados con fibra de carbono (CFRP). El estudio concluye resaltando el potencial del UHPC como opción viable para el refuerzo a flexión de estructuras de CR existentes y ofrece información perspicaz para fomentar el avance y la aplicación de esta tecnología en el sector de la construcción.

Palabras clave: Hormigón; Hormigón de Ultra Altas Prestaciones; Flexión; Recubrimiento; Refuerzo, Revisión.

INTRODUCTION

Concrete structures, such as buildings and bridges, are susceptible to various factors that can cause deterioration and weakening over the years.[1,2] One of the primary causes of the need for strengthening or repair of these structures is the rusting of the steel reinforcement. Corrosion is a common problem for the steel bars used to reinforce concrete,[3,4] particularly in hard conditions where they are exposed to moisture and salts over time. The changes to engineering practices and design codes may result in the incorporation of new safety standards and technologies over time.[5,6] It's possible that older buildings won't meet the more recent standards; in that case, they'll need to be strengthened or retrofitted to meet the requirements. Furthermore, alterations in the function of a structure might also necessitate reinforcement. Occasionally, a structure's original intended use may change, requiring it to support heavier loads or serve a different purpose. This change in usage may require strengthening to ensure the stability and safety of the structure.[7,8,9,10,11]

A number of conventional techniques for reinforcing and repairing concrete structures are explained in the passage. The use of intermediate supports, steel plate bonding, external pre-stressing, concrete jacketing, and steel jacketing are some of these methods. However, these methods have certain drawbacks, including making the structure heavier and larger and increasing the risk of corrosion and bonding failures because steel plates are used.[12,13,14,15,16,17]

Fiber-reinforced polymer (FRP) composite surface adhesion to concrete has gained popularity as a substitute. This method has quickly gained a lot of popularity, but it is not without problems. These consist of brittleness, susceptibility to bond failures, and brittleness in the presence of damp surfaces or high temperatures.[1,18,19,20,21,22]

More advanced and effective strengthening technologies that meet structural and architectural requirements are required due to the shortcomings of FRP composites and traditional methods. Ultra high-performance concrete (UHPC) strengthening is one such technology. Unmatched strength, durability, and low porosity characterize UHPC, a material that provides extra protection for concrete that has been damaged. Its outstanding performance makes it suitable for restoration work, especially on fire-damaged concrete structures.[1,23,24] Well-known for its unique qualities, UHPC is a contemporary type of concrete that has high workability, compressive strength, ductility, and resistance to environmental events.[25,26,27] These qualities have led to an increasing use of UHPC in a range of construction projects, such as high-rise buildings, long-span bridge girders, and defense, flight, and naval structures.[8,28]

The exceptional mechanical qualities of UHPC and its capacity to exhibit appropriate long-term behavior are responsible for this spike in usage.[29,30,31] UHPC has a number of better mechanical attributes. It can bear substantial pressure levels without cracking or deforming, for example, thanks to its remarkable compressive strength of more than 150 MPa.[32,,33] Furthermore, UHPC maintains a manageable post-cracking tensile strength greater than 5 MPa even after experiencing cracks.[34] Also, UHPC has a low permeability, which means that water and other substances are less likely to seep through. Its resilience to environmental influences and longevity are improved by this characteristic. Additionally, UHPC shows minimal creep and shrinkage,[23] which are alterations over time. These qualities guarantee that the concrete is stable and keeps its dimensions and shape over time. To further develop its characteristics, short fibers are often improved to UHPC in the range of 1,5-3 % by volume. These fibers strengthen the material's overall structure and increase its resistance to cracking.[8,28,35,36]

In recent years, numerous experimental and theoretical studies investigated the flexural behavior of reinforced concrete (RC) structures using UHPC layers. The strengthened objects among them were beams, T-beams, rectangular beams, etc. Additionally, common strengthening patterns included T-sided (tension side strengthening), C-sided (compression side strengthening), 2-sided (lateral side strengthening), 3-sided (three sides strengthening), etc.[37]

This review paper's objective is to provide a comprehensive and up-to-date analysis of the application of

UHPC to the flexural strengthening of RC members. While other research has examined the use of various strengthening techniques, the main focus of this paper is on UHPC as a novel strategy for enhancing the performance and load-bearing capacity of RC elements that are exposed to flexural stresses. The goal of this review is to significantly advance the field of structural engineering by offering a thorough analysis of UHPC's effectiveness in reinforcing RC members under flexural loading. It also seeks to provide researchers and engineers with useful information so they can maximize the performance of currently used reinforced concrete structures.

Experimental database

The use of UHPC to strengthen the flexural integrity of RC members has been the subject of numerous experimental studies in technical literature. The experimental database is summarized in detail in Table 1 with information on the status of RC beams, UHPC overlay properties, and experimental results of composite systems, with a total of 132 beams and panels included in the database, it provides a great deal of knowledge about the performance and effectiveness of UHPC as strengthening materials for members RC. It included a review of data from several researchers, such as the effect of the size of reinforced concrete, the compressive strength of normal strength concrete (NSC), the proportion of main reinforcement in reinforced concrete, and the yield strength of steel reinforcement. The pre-loading level for RC was also taken into account. For the reason of using UHPC in strengthening, it was briefly discussed the arrangement of UHPC, curing conditions, thickness, elastic modulus, tensile strength, compressive strength, reinforcement ratio in UHPC, steel fibers content, and interfacial preparation for the concrete member.

Figure 1 shows the typical four modes of strengthening configurations: C-zone, T-zone, 2-zone, and 3-zone. The C-zone shape places UHPC in the compressive side, while the T-sided configuration locates it in the tension side. The 2-zone configuration involves UHPC on the two sides of the cross-section, the three-zone configuration combines the last two strengthening configurations (T- zone and 2-side). The 2-zone configuration is primarily used for shear strengthening, while the 3-sided configuration is more efficient for flexural strengthening. However, the 2-sided configuration showed higher flexural strengthening efficiency compared to the T-zone configuration when concrete member surfaces were sandblasted and the UHPC was cast in situ directly on this NSC surface. The efficiency between the two configurations was similar when bonding produced UHPC laminate to the RC beams using epoxy adhesive. Engineers and researchers can now better understand the various variables and configurations that can affect the performance of the strengthened composite systems thanks to the research on the use of UHPC for RC structures.

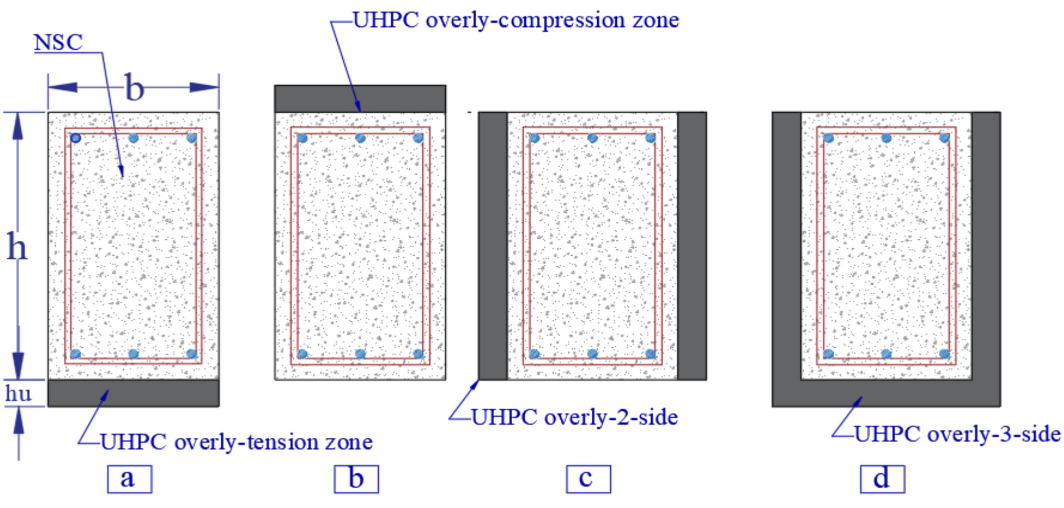

Figure 1. Four different strengthening shapes: (a) T-zone, (b) C-zone, (c) 2-zone, and (d) 3-zone [17]

Bond between UHPC and NSC

This study aims to investigate the effects of performing repairs on an old concrete surface by bonding a UHPC layer to it. The strength of the bond between UHPC and the preexisting concrete surface is what determines how effective this technique is.[38,39,56] Before bonding with UHPC, various surface preparation techniques were used on the old concrete surfaces to achieve a sufficient bond strength. These techniques included mechanical wire brush roughening, electrical grinder scratching, mechanical drill scabbling, and leaving the surface untreated to act as a smooth control surface.[57,58,59,60,61,62]

Table 1. Experimental Database

Ref.	No. of specimens	Dimensions of specimens (L ×b × h) (mm)	(MPa)	(MPa)	(%)	Overlay layout	Overlay thickness (mm)	(MPa)	Overlay reinforcement	Preparation of Interfaces
[40] 2010	4	4550 × 300 × 500	22	560	0,3	3-side	40	177	Un-reinforced	Sandblasting
[41] 2015	7	1584 × 150 × 300	51&70	-	-	T-side	51	168	Un-reinforced	-
[42] 2015	7	1500 × 100 × 200	30	415	1,3	T-side	20	196	Un-reinforced	Rough+ Epoxy
[43] 2016	3	2200 × 150 × 400	39,5	500	0,603	T-side & C-side	50	164	Un-reinforced	Rough
[28] 2016	7	3000 × 250 × 400	29,7	386	0,397	T-side & C-side	20, 40 & 60	156,3	Un-reinforced	aggregate
[44] 2017	6	1600 × 140 × 230	54	590	0,488	T-side, 2-side & 3-side	30	128	Un-reinforced	Sandblasting and Epoxy
[45] 2017	7	3200 × 150 × 250	20,6	470	0,905	T-side	50	204	Un-reinforced & Steel reinforced	Rough &Steel anchorage
[46] 2017	9	1600 × 300 × 100	33	501	1,885&0	T-side	20, 25, 32, 50 & 100	168	Un-reinforced & Steel reinforced	Rough
[47] 2017	5	3200 × 150 × 250	20,4	470	0,905	T-side	30	204	Un-reinforced & Steel reinforced	Rough+ Epoxy & Steel anchorage
[48] 2018	6	2200 × 150 × 250	30,9	500	0,603	T-side	50	136,5	Un-reinforced & Steel reinforced	Rough
[49,50] 2016,2018	12	1500 × 100 × 200	35	415	0,57, 0,9&1,3	T-side	20	170	Un-reinforced	Rough+ Epoxy
[51] 2018	15	1500 × 100 × 200	35	415	0,785	T-side	5, 8, 10, 12 &15	122,5	Un-reinforced	Rough+ Epoxy
[39] 2019	4	3200 × 2000 × 280	60,2	400	0,729	T-side & C-side	50	130	Un-reinforced & Steel reinforced	Rough &Steel anchorage
[52] 2021	4	1500 × 100 × 200	35	435	0,559	T-side	5, 10 &15	118	Un-reinforced	Rough+ Epoxy
[1] 2022	16	3200 × 150 × 250	20,40&60	460	0,31,0,67,1,04 &1,25	T-side	30	204	Un-reinforced & CFRP reinforced	Rough
[53] 2023	6	2800 × 200 × 400	54,3	435,5	0,318	T-side	50	157,2	Steel reinforced& strand	Rough
[54] 2023	6	3200 × 150 × 250	37,3	593,3	0,487	T-side	30 &50	130,3	Un-reinforced & CFRP reinforced	Rough+ Epoxy+ CFRP sheet
[55] 2023	8	2000 × 100 × 300	32,6	520	0,599	T-side	30 &40	124	Steel reinforced	Rough+ Epoxy

The following conclusions were drawn from the study:

1. The need for proper substrate surface preparation was demonstrated by the results. This is necessary to ensure an effective connection between the old concrete and the UHPC. Greater bond strengths were produced by all surface planning techniques when compared to the reference specimens, which underwent no preparation. The mechanical interlocking and adhesion between the two materials are improved with sufficient surface roughening, which enhances bond performance overall.(58,59)
2. Slant Shear Strength Bonding: The interfacial failure only occurred after the impact of the old concrete substrate, indicating that the strength of the bond in the slant shear test was appropriately high. Before the bond failed, the old concrete member showed signs of cracking and crushing, demonstrating a strong bond between the UHPC overlay and the surface member.(60)
3. Scabbling Offers Highest Shear Strength: Scabbling offered the highest shear strengths with a fully uniform failure mode among the surface preparation techniques. The bond strength was significantly higher than the old concrete member because the failure occurred inside the old concrete and there was no interfacial separation or debonding between the substrate and UHPC. Old Concrete with Effective UHPC Bonds: The results of the splitting tensile test indicated that the old concrete substrate was where most of the failure occurred. Using wire brush and scabbling techniques, where the bond behaves almost monolithically, the UHPC bonded very strongly and competently with the old concrete, according to this evidence.(58,59,62)

The study's overall conclusion highlights the significance of surface preparation for achieving successful bonding between UHPC and aged concrete layers during repair work. The findings show that UHPC can successfully bond to aged concrete substrates, offering a promising method for strengthening and repairing concrete members.

Investigated parameters

Thickness of UHPC

These beams' behavior was impacted by the overlay thickness (h), and their load-deflection responses were discussed. The pre-yield stiffness of the beam is adequately increased when using plain UHPC overlay, but the load at the first detectable flexural crack is not significantly altered. an increase in ultimate load (Pu) of 8 % to 11 %.(54)

The ultimate load-carrying capacity of the structure being strengthened typically increases slightly by about 1 % to 20 % when the overlay thickness is increased in plain overlays (overlays without reinforcement), as shown in figure 2.(38,51,53) As the UHPC overlay thickness increases, the stiffness of strengthened RC beams increases as well. Additionally, the results showed that as UHPC overlay thicknesses increase, the deflection of all strengthened beams at yield and ultimate loads decreases.(38,46,52,54) It has been noted that when the thickness of the UHPC overlay increases, the quantity of widespread flexural cracks decreases.(55)

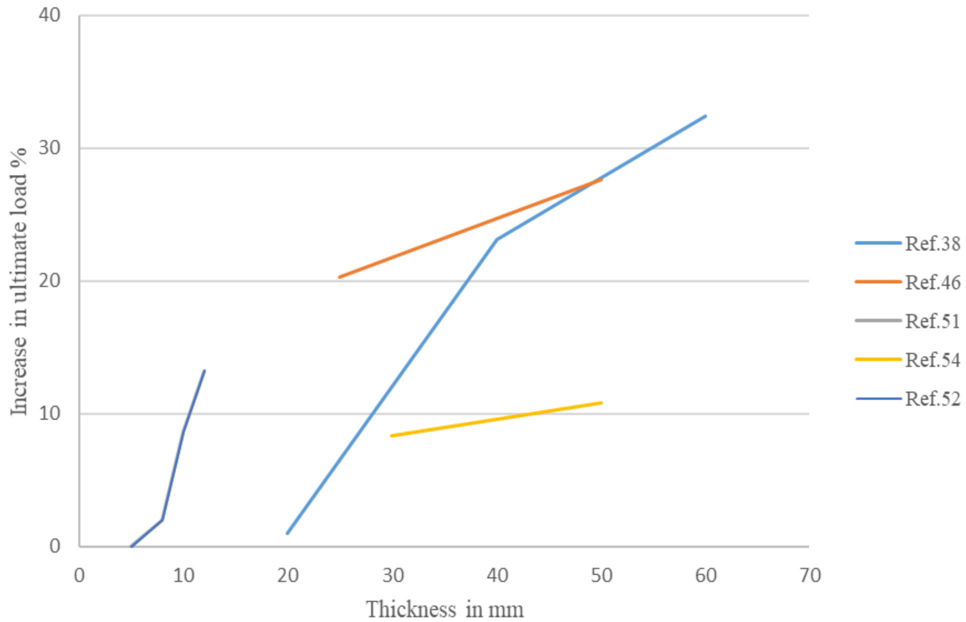

Figure 2. Increase in ultimate load capacity against UHPC overlay thickness(38,46,51,52,54)

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Beam-UHPC overlay interface

Six different types of interfacial preparation methods used in strengthening RC members with UHPC overlays were discussed here. These methods are aimed at improving the bond between the UHPC overlay and the concrete substrate, where are methods as follows, *(a) rough preparation* using an air chipping hammer, a high-pressure water jet and etc.[43,46,58] *(b) Aggregate preparation* method involved spraying a chemical retarder on the concrete substrate during casting.[38] *(c) Rough & Epoxy adhesion* method combined roughening and epoxy adhesion. It involved creating grooves on the tension surface of RC beams using an angle grinder and applying epoxy adhesive.[42,45,47,50,51,55] *(d) Epoxy adhesion and sandblasting (SB)* were applied separately. The concrete surface was sandblasted to a certain depth, and epoxy adhesive was applied to improve the bond.[40,44] *(e) Rough and Steel anchorages*, this method combined roughening and using studs for mechanical anchorages.[39,45,47] *(f) Epoxy and CFRP U-Shape*, this method was easy and providing good bond,[54] but it is worth noting that its cost may be relatively higher when compared to other alternatives.

Table 1 shows that, compared to the steel anchorage method, the bonding technique performed better than the use of epoxy, with only a slight increase in maximum load. Epoxy was selected as the strip overlay material in the strengthened structure members due to its remarkable curing speed, remarkable bond strength, ease of application, and durability. Because of these qualities, epoxy maybe the best option to use when restoring concrete surfaces.

Presence of reinforcement in UHPC overlay

Using steel reinforcement

This section discusses the use of steel reinforcement in UHPC overlays and how it impacts the overall behavior of the strengthened members. In order to enhance the UHPC layer's mechanical performance, some studies have looked into the possibility of adding steel reinforcements. Steel reinforcements have a tension-stiffening effect that causes the UHPC layer to manifest clearly strain hardening behavior and more widely dispersed macro cracks.[39,35,45,46,47] The load-bearing capacity of the strengthened beams has been demonstrated to be significantly increased by the addition of steel reinforcements to the UHPC layer, as depicted in *Figure 3*. The improved mechanical properties of the UHPC with steel reinforcement and the tension-stiffening effect are credited with this improvement.[45,46,53,55] Different steel reinforcement diameters have been used in the UHPC overlays in various studies. Examples include:

- Three bars with an 8 mm diameter in [45] and [47] (see figure 4 A and B).
- Two bars with a 10 mm diameter in [48] and [55] (see figure 4 C)).
- Three bars with a 12 mm diameter in [53] (see figure 4 D).

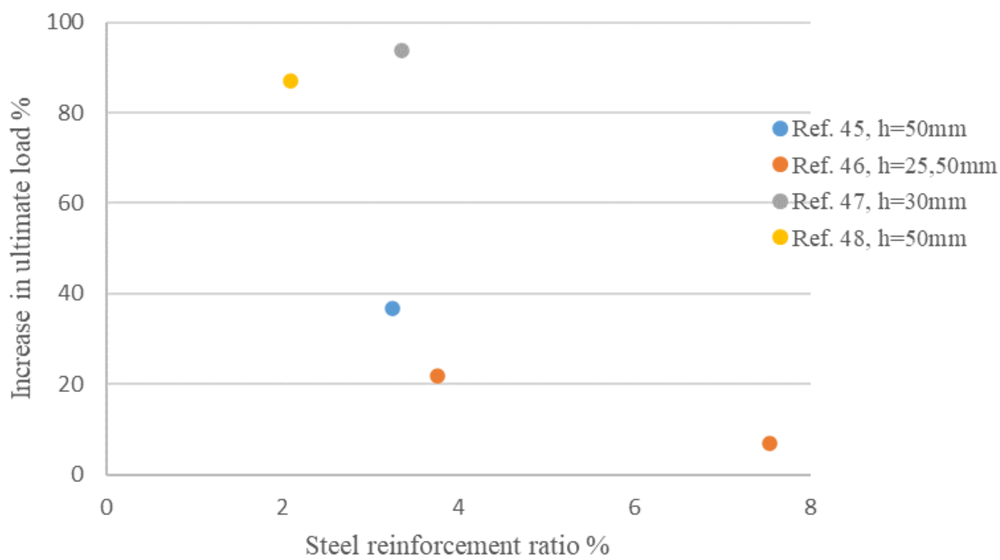

Figure 3. Increase in ultimate load capacity against steel reinforcement ratio in UHPC overlay with different thickness(h) [45,46,47,48]

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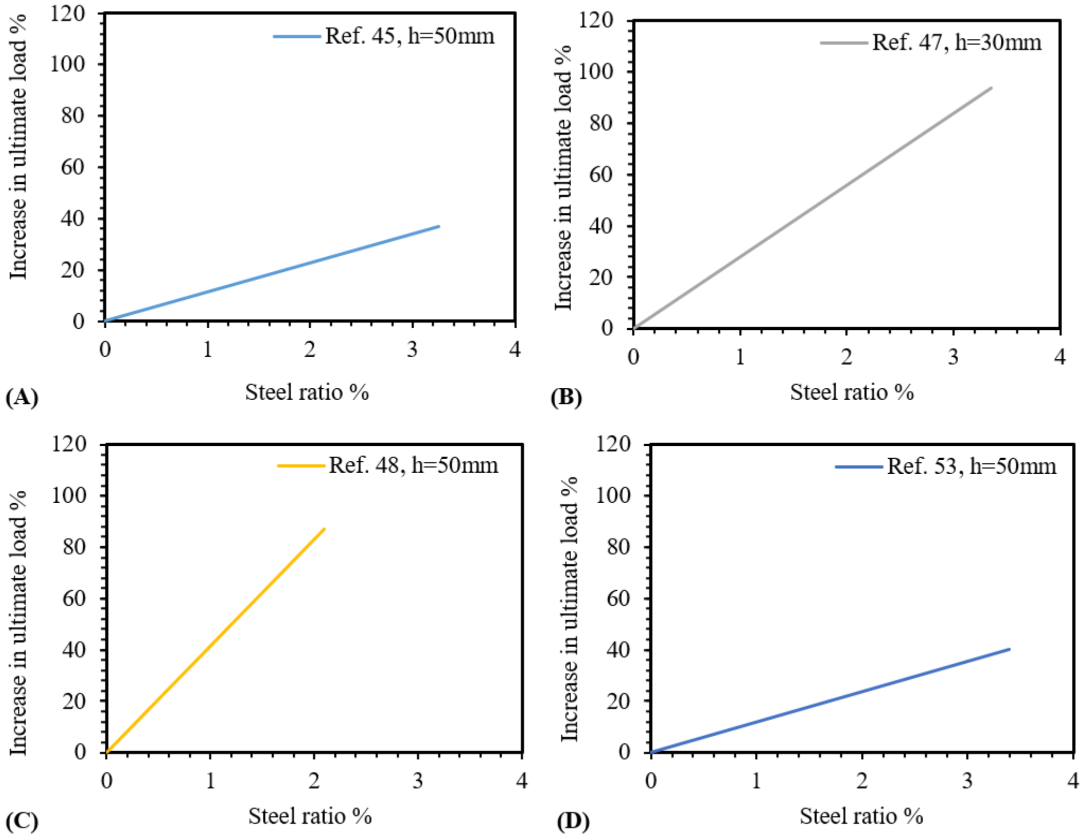

Figure 4. Increase ultimate load capacity against steel reinforcement ratio in UHPC overlay for various thicknesses obtained from different references, A,[45] B,[47] C[48] and D[43]

Using FRP reinforcement

As previously mentioned, the utilization of steel reinforcement in UHPC overlays resulted in a significant increase in the ultimate load and enhanced the overall behavior of the strengthened beams. However, there are some drawbacks associated with using steel reinforcement in UHPC overlays, including:

(a) Reinforcement contribution to tensile forces, the carbon-FRP (CFRP) bars embedded within the overlay provide additional tensile strength to the system. This helps in resisting the tensile forces that develop due to bending or external loads, which is especially crucial in the case of concrete elements like beams that are prone to tensile cracking.[1,54]

(b) bridging of overlay cracks and tensile contribution: The CFRP-reinforced overlay effectively "bridges" over cracks that might form in the overlay due to loading. This bridging action helps prevent crack propagation, effectively acting as a barrier to stop cracks from widening. Moreover, this bridging effect enhances the overall tensile contribution of the overlay, as it can distribute loads more effectively and prevent localized cracking.[1,54]

Previous studies demonstrated that reinforcing the overlay with CFRP bars resulted in a remarkable increase in the ultimate load (157 %) when compared to a plain UHPC overlay.[54]

CONCLUSIONS

This study provides a comprehensive review of recent research on the UHPC-enhanced flexural strengthening of RC beams. Analytical models that are based on the experimental database's estimations. The application of UHPC has demonstrated considerable potential to increase the flexural strength of RC beams.

1. The bond between UHPC and NSC was found to be one of the most important factors governing the effectiveness of the UHPC strengthening technique.
2. Increasing thickness of UHPC caused a significant increase in the ultimate load ranged from 20 % to 60 % when the thickness of UHPC changed from 30 to 50 mm.
3. Presence steel reinforcement in the UHPC layer in tension zone caused a noticeable increase in ultimate load ranged from 37 % to 94 % depending on the steel reinforcement ratio in UHPC, thickness of UHPC layer and amount of steel reinforcement in the strengthened beams.
4. Using CFRP as a reinforcement in UHPC overlay caused superior improvement in ultimate load compared to steel reinforcement. Particularly, using CFRP in UHPC overlay increase the ultimate load of

the strengthened beam with 157 % compared to the beam strengthened with plain-UHPC overlay with the same thickness.

RECOMMENDATIONS

1. It may be a worthy option to investigate the effects of using UHPC with fibers content 2-3 %.
2. Based on the effects of increasing the overlay thickness, most researchers recommend using a thickness of between 30 and 50 mm for the UHPC overlay.
3. It is recommended to use epoxy and roughened concrete member surfaces for future UHPC strengthening applications in order to install UHPC strips directly in site rather than using cast in place UHPC layers.
4. Applying GFRP and CFRP to reinforce UHPC overlays with various ratio of reinforcement and thicknesses of UHPC to make an optimization for the best combination in terms of strength and cost.

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CONFLICT OF INTEREST

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