Paper ID: CE 0344

Utilization of Ultra High Performance Fiber Reinforced Concrete (UHPFRC) in Bridge Decks- A review

N. J. Monica[1], A. Mim, M. H. Khatun[1], S. Saha[1], A. H. M. Adyeel[1], K. S. Shahnaz[1]

[1]Department of Civil Engineering, RUET, Bangladesh

Abstract

In recent years, Ultra High-Performance Fiber-Reinforced Concrete (UHPFRC) has attracted considerable interest as a serviceable material for bridge deck construction. The mechanical properties of UHPFRC is comparatively better than normal concrete which can be a good solution for impact load resistance. That is why UHPFRC can be a great choice. In the present study the use of UHPFRC and its various properties has been assessed. Compressive and tensile strengths, fatigue behavior, durability, blast resistance, and rehabilitation of ultra-high-performance fiber-reinforced concrete (UHPFRC) are covered in this review. The review shows the various ways that UHPFRC can be used in bridge decks and also gives examples from around the world. This paper also reviews the problems and limitations of using UHPFRC to build bridge decks, and recommends future research that could move the subject forward. The study is an excellent resource for scholars, engineers, and professionals focused on constructing UHPFRC bridge deck.

Keywords: *UHPFRC in bridge deck; blast resistance; impact load; fatigue*.

1 Introduction

Growing interest has been shown recently in the creation and application of cutting-edge building materials that can improve the strength and structural performance of bridge decks. With its remarkable mechanical qualities and improved durability features, Ultra High-Performance Fiber Reinforced Concrete (UHPFRC) has distinguished itself among these materials as a prospective alternative. A deck is the top most surface of a bride over the vehicles run. The weights from automobile traffic supported by bridge decks, which are continually put under a variety of mechanical and environmental stresses. Heavy traffic volumes and dynamic effects like vibrations are some of these pressures. The performance criteria for bridge deck applications are frequently not fully met by traditional concrete materials, which causes problems including cracking, premature deterioration, and expensive maintenance and repair.

The practical and effective use of UHPFRC in bridge decks has obtained significant attention in recent years due to its exceptional properties. This review paper aims to provide a comprehensive analysis of the compressive and tensile strength, fatigue behavior, durability, blast resistance, rehabilitation and practical applications of UHPFRC in bridge deck construction. This review paper also includes limitations in applications of UHPFRC. This review paper aims to provide useful information for researchers, engineers, and practitioners involved in the design, construction, and maintenance of bridge deck structures by combining the existing knowledge.

In general, this review study aims to advance knowledge of UHPFRC as a practical substitute material for bridge deck construction. It attempts to clarify the potential advantages by examining the available literature, ultimately encouraging the adoption of this material in future bridge engineering techniques.

2 Compressive & Tensile Strength:

As the bridge deck undergoes various loads and environmental impact directly, it requires higher mechanical strength for a long-term lifespan. Compressive and tensile strength is one of the major concerns among them. According to AASHTO, nowadays up to 70 MPa compressive strength is accepted to use in bridge construction.

In this regard, using steel fiber gives a better result than that. Mixing proportion of about 2% steel fiber with cement, silica fume, silica sand, Ground Granulated Blast Furnace Slag (GGBS), and water for UHPFRC and the same proportion with 0% steel fiber for UHPC was cast into molds. The test was conducted under the BS standard and ASTM standards. At 28 days it gives the best result of about 150.56 MPa compressive strength (Hassan et al., 2012).

Using 3% of steel fiber gives 148.1 MPa (Máca et al., 2014). So, 2% steel fiber is the best mixing proportion for maximum compressive stress development. The compressive behavior of UHPFRC and UHPC, which resulted in the identical stress-strain relationship before peak load, is shown in the figure below. However, after peak load, UHPFRC exhibited softening behavior, whereas UHPC exhibited brittle behavior.

Table 1. Comparison between UHPFRC and UHPC of their mechanical properties

	Mixing of Fiber	**Highest Compressive Strength in UHPFRC**	**Highest Compressive Strength in UHPC**	**Best Result**
Compressive Strength	2% Steel Fiber for UHPFRC and 0% for UHPC	150.56 (MPa)	121.32 (MPa)	UHPFRC
	3% Steel Fiber for UHPFRC and 0% for UHPC	148.1 (MPa)	132.4 (MPa)	UHPFRC
	4% Steel Fiber for UHPFRC and 0% for UHPC	134.8 (MPa)	61 (MPa)	UHPFRC
Tensile Strength	2% Steel Fiber for UHPFRC and 0% for UHPC	9.07 (MPa)	5.36 (MPa)	UHPFRC
	3% Steel Fiber for UHPFRC and 0% for UHPC	10.9 (MPa)	6.6 (MPa)	UHPFRC
	4% Steel Fiber for UHPFRC and 0% for UHPC	10.5(MPa)	4.90 (MPa)	UHPFRC

*UHPFRC- Ultra high performance fiber reinforced concrete; UHPC- Ultra high performance reinforced concrete

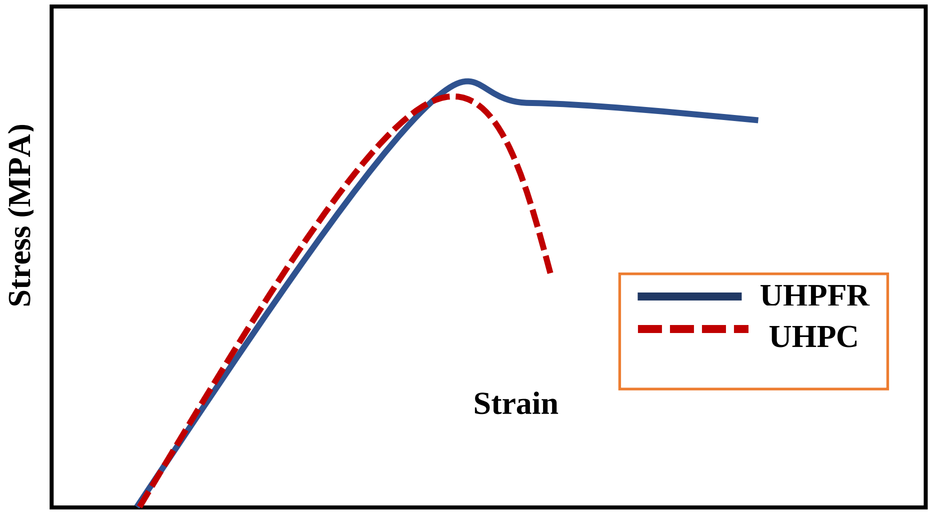

Figure 1: Stress-strain relationship of UHPFRC & UHPC in Compression (S. et al., 2014)

When it comes to tensile strength, the UHPC specimen behaves elastically up to its maximum strength before a sudden strain softening follows. In contrast, when it comes to UHPFRC, however, the maximum strength is followed by a gradual strain softening in which the preexisting fibers regulate the softening stage. UHPFRC had around double the tensile strength of UHPC (Hassan et al., 2012). The tensile strength was higher when 3% of the volume was made up of fibers. Therefore, 2 to 3% by volume of fiber is the ideal amount to include in the UHPFRC combination to get the best tensile strength. (Máca et al., 2014).

Due to its remarkable durability and water tightness, 4%-UHPFRC was used as the top layer of the hybrid slab in this case. It included 4%. Straight steel fibers with unique w/b ratios of 0.20 and 0.19 made up 4% of the UHPFRC. UHPFRC was given a post-peak softening behavior and a pre-peak strain-hardening behavior with the help of a specific particle-size optimization, a low w/b, and a high fiber dosage. A higher tensile strength was attained in UHPFRC-4% as a result of the more steel fibers used in the material. (Verger-Leboeuf et al., 2017).

3 Blast Resistance

The blast resistance of concrete refers to its ability to withstand and mitigate the effects of an explosion. It is a measure of how well concrete can absorb and dissipate the energy generated by a blast, minimizing structural damage and protecting occupants and surrounding infrastructure (Alhadid et al., 2014). In Table 2 a comparison between normal concrete, HSC, UHPFRC & UHPFRC with basalt mesh is shown (Foglar et al., 2017). The internal damage of concrete deck slabs using UHPFRC was much less than HSC. The internal damage of UHPFRC with basalt mesh was greater than regular UHPFRC. None of the UHPFRC specimens was noticeably breached during blast loading, whereas HSC with HSS fibers were breached.

Table 2. Specimen details and Comparison of blast performance of concrete slabs (Foglar et al., 2017)

Specimen no.	**01**	**12**	**13**	**14**	**15**	**16**	**17**	**FEM model in LS-DYNA**
Materials	**Normal Concrete**	**HSC**	**HSC**	**HSC**	**HSC**	**UHPF RC**	**UHPFRC with Basalt mesh**	**Sp.15 with & without Basalt mes h**
Compressive St rength [MPa]	–	68.5	66.9	73.2	76.1	129.5	125.8	–
Flexural Tensile Strength [MPa]	–	8.92	8.89	8.19	10.71	13.06	10.73	–
Damage of Total Volume	–	6.3%	9.6%	7%	5.9%	2.2%	3%	–
Punctured Area [top surface]	100%	51%	108%	56%	37%	–	2%	–
Permanent Defl ection	100%	110%	–	113%	161%	123%	123%	–
Volume of Crushed Concrete	100%	72%	115%	82%	71%	28%	33%	–
Fracture Energy [N/m]	–	13,409	13,235	12,920	13,976	18,853	10,049	13,690

From these experimental data, it is established that UHPFRC has better performance than normal concrete and concrete with other normal fibers in blast resistance and other important behaviors (Hajek et al., 2016)

4 Fatigue Behavior:

Fatigue in RCC is depicted by progressive permanent internal damage of RCC under fluctuating stress due to repeated loads (Sain er al., 1978). The required fatigue resistance can be enhanced by adding a thin layer (30-50 mm) of R-UHPFRC (UHPFRC containing steel rebars) on the top surface of the deck slab. T. Makita et al (Makita et al., 2012) conducted an experiment taking maximum fatigue force F_{max} between 40% and 60% of the ultimate static strength F_u = 90kN. F_{min} was taken 10% of F_{max} and fatigue limit was S= F_{max}/F_u.

The specimens which sustained more than 10 million fatigue cycles, are denoted as run-out. From the experiment, the maximum fatigue limit was S=0.5 or 50% of F_u where the value of fatigue limit normally varies within 0.25 to 0.60 according to Wöhler Curves (S-N Diagram).

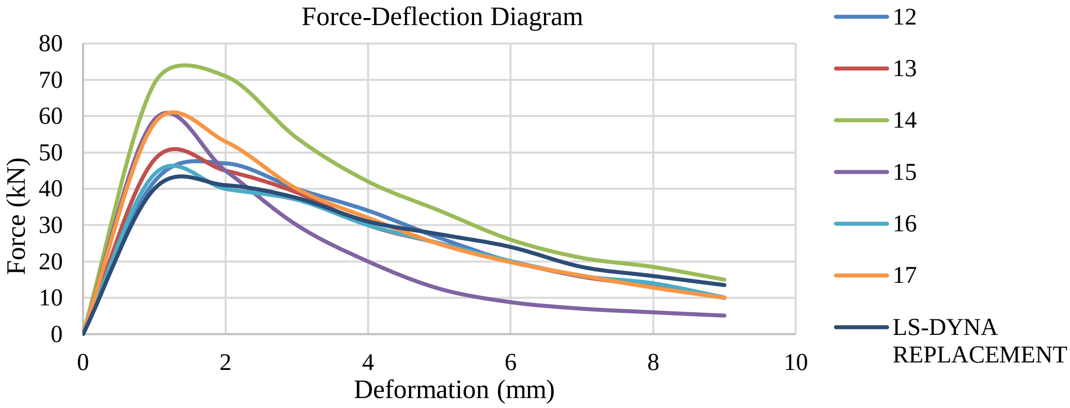

Figure 2. Force-deflection diagrams of concrete mixtures from the experimental program and from numerical simulation (Foglar et al., 2017)

5 Durability:

The ability of concrete and cementitious composites to maintain their original desired engineering properties over centuries in harsh environments is referred to as durability. Since concrete is characterized as a porous composite material in terms of moisture and chemical penetration into its pores, its durability is greatly influenced by micro- and macrostructures that limit the air, water, and ion permeability of the material. UHPC contains a variety of fine materials as well as very dense structures and low permeability. Disabilities such as chemical and frost resistance, are greatly enhanced by the limited transport and presence of water and ions in UHPC structures (Zhou et al., 2018).

Due to the use of a low water-to-binder ratio (W/B) of about 0.2 and a high volume of small particles, ultra-high-performance concrete (UHPC) is more durable than conventional concrete (CC) and high-performance concrete (HPC). It is an innovative composite material that could be well-suited for concrete structures exposed to harsh environments (Li et al., 2020). By optimizing the particle packing density of the cementitious matrix, ultra-high-performance concrete (UHPC) achieves exceptional strength properties. The biggest advantage of the material, which is undoubtedly the dense matrix, is that it has remarkable durability characteristics (Alkaysi et al., 2016).

Table 3: Characteristic durability values for UHPC, HPC, and Normal Strength Concrete (Schmidt et al., 2005)

Indicator	**Ordinary Concrete C 35 EN 206**	**High-Performance Concrete C 100/115 EN 206**	**Ultra-High Perf. Concrete**
Total porosity [%]	app. 15	app. 8	4-6
Capillary pores [%]	app. 8	app. 5	1.5-2.0
Nitrogen permeability [m^2]	10^{-16}	10^{-17}	$<10^{-18}$
Chloride-ion diffusion (6h quick-migration test)$^{2)}$ Depths of intrusion [mm]	23	8	1
Carbonation depth (after 3 years) in mm (20°C, 65% r. humidity)	7	4	1.5
Freeze-salt-resistance (scaling in [g/m^2])$^{1)}$	< 1500 (air-entrained)	150 (air-entrained)	20…50 water … heat cured
Water absorption factor$^{3)}$	60	11	1

1) CDF- test, 28 cycles, limit 1500 g/m^2 2) (Tang and Nielsson 1992) 3) DIN 52617

Michael Schmidt et al. has shown in the table that Ultra-High-Performance Concrete (UHPC) has low porosity, low permeability, low chloride-ion diffusion, and low water absorption factor than Ordinary Concrete and High-Performance Concrete (Schmidt et al., 2005). For having these qualities, UHPC is more durable than the other ones.

6 Rehabilitation

Rehabilitation refers to the process of repairing or restoring deteriorated or damaged structures. When it comes to the rehabilitation of structures, UHPFRC offers several advantages over conventional concrete. The extension of a structure's lifecycle at a reasonable cost makes the rehabilitation of existing reinforced concrete structures with a UHPFRC layer effective. UHPFRC exhibits high tensile strength, low permeability, ductility, early hardening and act as a waterproofing member in bridge deck. Rebars guarantee the UHPFRC layer's high strain capacity and prevent the emergence of macrocracks (Moreillon et al., 2013) (BASTIENMASSE et al., 2013). In addition, UHPFRC's low permeability and mechanical properties enable diverse applications on a variety of constructions, demonstrating its efficacy in a range of conditions. Although frequently used on bridges, its qualities could also be advantageous for curbs, building slabs, or constructions in maritime conditions. The use of UHPFRC at higher slopes, which may be cast to produce satisfactory results even at 12% inclination, is particularly encouraging since it allows for the rehabilitation of areas that are difficult to reach using conventional methods. Precast technologies are effective and affordable, but to fully realize their potential, large-scale processing must be used (Martin-sanz et al., 2016). The Buna Bridge's rehabilitation using UHPFRC slab attached to steel girders by steel shear studs, the bridge was taken out of service in 2010. There was a 20% decrease in deflection and a 40% reduction in stress. A series of experimental static and dynamic tests were performed for the purpose of rehabilitation and strengthening the structure, and the UHPFRC strengthening approach reduced strains by up to 40% (Mia, 2020).

7 Limitations in Applications of UHPFRC

Although UHPC is frequently utilized in the planning and building of bridges, there are still considerable restrictions and unknowns regarding the material's applicability and qualities.
(1) It can be said that one of the main issues with the mix design of UHPC is its relatively high cost.
Numerous studies have been done to optimize the UHPC mix and reduce the cost of UHPC by substituting less expensive materials for cement and silica fume.
The literature that is currently available, however, seldom ever compares the relative economic advantages of various UHPC configurations.
For next investigations, a thorough cost analysis and evaluation of UHPC are required.
(2) A considerable increase in compressive and tensile strength is seen when steel fibers are added to UHPC, according to extensive study. On the other hand, goods made of concrete composition have yielded conflicting outcomes. Therefore, additional experimental research is required to get more thorough information regarding the impact of fiber addition on the mechanical properties of UHPC.
(3) Studies have shown that it is possible to replace NSC with UHPC in bridge applications, but solutions to lower UHPC costs have not yet been developed. This highlights the need for more research on this subject to broaden and prolong the usage of UHPC in bridges.
(4) To extend the use of UHPC in jointless bridges, further studies are needed on the mechanical properties and failure mechanism of UHPC used for link slabs.
(5) Despite the numerous benefits of jointless bridge decks, there are few specifications and design guidelines available in the United States and no consistent set of design standards and procedures for such bridges.(Xue et al., 2020).

8 Conclusion

The review of the paper covered the compressive strength, tensile strength, blast resistance, and rehabilitation of UHPFRC. It was emphasized that UHPFRC performs better than traditional concrete in each of these areas. UHPFRC is ideally suited for bridge decking due of its remarkable strength and ductility. UHPFRC's enhanced toughness was also covered, emphasizing its resilience to environmental elements such freeze-thaw resistance, total porosity, and chloride-ion diffusion. UHPFRC is a fantastic option for structures in hostile or corrosive settings because of its longevity. The research paper also discussed UHPFRC's possible drawbacks, including its expensive price, convoluted manufacturing process, and requirement for specialist equipment. It was stressed that

UHPFRC's considerable advantages exceed these drawbacks, particularly for crucial infrastructure projects where durability and performance are crucial considerations.

Due to its superior mechanical qualities and increased durability, UHPFRC is, in summary, a promising material for building projects like bridge decking. UHPFRC has the potential to transform the construction industry and pave the way for cutting-edge structural solutions thanks to its capacity to handle heavy loads, withstand environmental variables, and deliver long-lasting performance. It is urged to do additional research and development in UHPFRC to solve current issues and investigate novel applications that will ultimately result in safer, more robust, and more sustainable infrastructure.

Reference

Alhadid, M., Soliman, A. M., Nehdi, M. L., & Youssef, M. A. (2014). *Critical overview of blast resistance of different concrete types*. *January*. https://doi.org/10.1680/macr.13.00096

Alkaysi, M., El-tawil, S., Liu, Z., & Hansen, W. (2016). Effects of silica powder and cement type on durability of ultra high performance concrete (UHPC). *Cement and Concrete Composites*, *66*, 47–56. https://doi.org/10.1016/j.cemconcomp.2015.11.005

Bastienmasse, M., & Brühwiler, E. (2013). *Concrete bridge deck slabs strengthened with UHPFRC UHPFRC in tension*.

Foglar, M., Hajek, R., Fladr, J., Pachman, J., & Stoller, J. (2017). Full-scale experimental testing of the blast resistance of HPFRC and UHPFRC bridge decks. *Construction and Building Materials*, *145*, 588–601. https://doi.org/10.1016/j.conbuildmat.2017.04.054

Hajek, R., Foglar, M., & Fladr, J. (2016). Influence of barrier material and barrier shape on blast wave mitigation. *Construction and Building Materials*, *120*, 54–64. https://doi.org/10.1016/j.conbuildmat.2016.05.078

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). *Construction and Building Materials*, *37*, 874–882. https://doi.org/10.1016/j.conbuildmat.2012.04.030

Máca, P., Sovják, R., & Vav, T. (2014). *Resistance of ultra high performance fibre reinforced concrete to projectile impact*. *75*, 97–108. https://doi.org/10.2495/978-1-84564-879-4/010

Makita, T., & Brühwiler, E. (2012). Fatigue behaviour of bridge deck slab elements strengthened with reinforced UHPFRC. *Bridge Maintenance, Safety, Management, Resilience and Sustainability - Proceedings of the Sixth International Conference on Bridge Maintenance, Safety and Management*, 1974–1980. https://doi.org/10.1201/b12352-292

Martin-sanz, H., & Chatzi, E. (2016). *The use of Ultra High Performance Fibre Reinforced cement-based Composites in rehabilitation projects : a review The Use of Ultra High Performance Fibre Reinforced Cement-Based Composites In Rehabilitation Projects : July*. https://doi.org/10.21012/FC9.219

Mia, M. M. (2020). *A state-of-the-art review of the application of ultra-high-performance fiber-reinforced concrete in bridge engineering*. 978–984.

Moreillon, L., & Menétrey, P. (2013). *Rehabilitation And Strengthening of Existing RC Structures With Uhpfrc : Various Applications*. *1*, 127–136.

S., N., M.A, I., & M., A. (2014). Possibility to Improve Strength and Structural Stability of Bridge Deck Slabs by Using Ultra High Performance Fiber Reinforced Concrete. *IOSR Journal of Mechanical and Civil Engineering*, *11*(3), 79–87. https://doi.org/10.9790/1684-11327987

Sain, T., & Kishen, J. M. C. (1978). *Residual fatigue life of RCC : Deterministic & probabilistic approach*. *1963*.

Schmidt, M., & Fehling, E. (2005). *Ultra-High-Performance Concrete : Research , Development and Application in Europe*. *5*(January 2005).

Verger-Leboeuf, S., Charron, J.-P., & Massicotte, B. (2017). Design and Behavior of UHPFRC Field-Cast Transverse Connections between Precast Bridge Deck Elements. *Journal of Bridge Engineering*, *22*(7), 04017031. https://doi.org/10.1061/(asce)be.1943-5592.0001064

Xue, J., Briseghella, B., Huang, F., Nuti, C., Tabatabai, H., & Chen, B. (2020). Review of ultra-high performance concrete and its application in bridge engineering. *Construction and Building Materials*, *260*, 119844. https://doi.org/10.1016/j.conbuildmat.2020.119844

Zhou, Z., & Qiao, P. (2018). Durability of ultra-high performance concrete in tension under cold weather conditions. *Cement and Concrete Composites*. https://doi.org/10.1016/j.cemconcomp.2018.08.019