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A state-of-the-art review of the application of ultra-high-performance fiber-reinforced concrete in bridge engineering

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ABSTRACT: Extensive research and development efforts over the last three decades have been made to improve the strength of concrete, resulting in the emergence of ultra-high-performance concrete (UHPC). UHPC is generally characterized as concrete with a compressive strength exceeding 150 MPa, and improved deflection and high flexural strength. However, one of the drawbacks of UHPC is the brittleness, which creates many problems in its application in bridge construction. To overcome this problem, fibers are added in the concrete mixture which is called ultra-high-performance fiber-reinforced concrete (UHPFRC). This innovative concrete offers superior strength, improved ductility, fracture toughness, and energy absorption capacity. In this paper, a state-of-the-art review of UHPFRC is presented in which the development of and recent progress with regard to UHPFR Care highlighted. Applications of UHPFRC in a few recent bridge projects are also presented, along with a brief description of retrofitting and repair of bridge components and fatigue behavior of UHPFRC.

1 INTRODUCTION

Many bridges across North America have reached their expected lifespan, and some have shown signs of accelerated deterioration (Lachance et al. 2016). Use of deicing salts and an increase in traffic volume are two of the key factors in this deterioration, with concrete bridge decks being prone to corrosion, delamination, and cracking. Over the years, many methods have been proposed to protect against this deterioration. One of the methods is to use a thick concrete cover where the goal is to increase the time for chlorides to diffuse before they reach the reinforcing bars and cause corrosion. But a thicker concrete cover increases the crack width due to shrinkage, thermal effects, and increased traffic loads. The use of epoxy-coated or FRP bars have their own limitations, such as brittle failure due to debonding. It should be noted, moreover, that none of the above solutions address the cracking issue (Lachance et al. 2016). Stainless steel (SS) rebar is a preferable option due to its high ductility and excellent corrosion resistance (Billah & Alam 2012, Rossi 2014, Islam et al. 2020). However, the price of SS rebar is much higher compared to the mild steel rebar which will increase the overall project cost.

In this context, UHPFRC has emerged in recent years as a promising solution in bridge construction due to the low permeability and higher durability provided by steel fibers. According to L'Association Française de Génie Civil (AFGC) (2013), UHPFRC is defined as concrete with a compressive strength between 150 MPa and 250 MPa and a tensile strength of at least 8 MPa. UHPFRC is normally in the form of a super-plasticized, fiber-reinforced, silica fume–cement mixture having a low water-cement ratio with very fine quartz sand. UHPFRC has attracted much attention from researchers and engineers around the world for its excellent mechanical properties (Yoo & Yoon 2016).Also, the structural weight is significantly reduced due to the high strength characteristics of UHPFRC. As a result, the weight of a UHPFRC structure is about ½ to 1/3 of the weight of a conventional reinforced concrete structure at identical external loads (Tam et al. 2012). UHPFRC addresses many of the shortcomings of normal strength and high-strength concrete. The different families of UHPFRC are related as illustrated in Figure 1, with the properties of each corresponding to the given combination of the three concrete technologies: fiber-reinforced concrete (FRC), self-compacting concrete (SCC), and high-performance concrete (HPC).

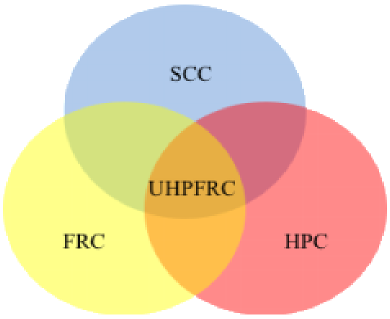


Figure 1. Various types of innovative concretes (Camacho 2013).

In the 1970s, ultra-high-strength cement pastes were introduced by Yudenfreund et al. (1972) and Roy et al. (1972), the former having developed a cement paste with a compressive strength of 230 MPa. Roy et al. (1972), meanwhile, obtained a cement paste with a compressive strength of 510 MPa. With the development of pozzolanic admixtures and superplasticizers, ultra-high-strength and low-porous concretes were developed by Bache (1981) and Birchall et al. (1981). This concrete technology came to be referred to as densified with small particles (DSP), typically having a compressive strength in the range of 120 to 270 MPa and featuring a macro-defect free (MDF) paste with a compressive strength greater than 200 MPa. Finally, reactive powder concrete (RPC), as a direct forerunner to UHPFRC, was developed by Richard &Cheyrezy (1995). In their study, short steel fibers were incorporated into concrete (at a proportion of 1.5% - 3% by volume) for the purpose of achieving ultra-high strength. They were thus able to develop a concrete exhibiting a compressive strength in the range of 200 to 800 MPa. After optimizing the design at Lafarge Research Center, Ductal®, the first commercial UHPFRC was developed in the late 1990s (Batoz&Behloul 2011). Then, the BSI/CERACEM® technology was developed in the 1990s; this technology increased the application of UHPFRC in both new structures and repair projects. In the following decade, cement company, Vicat, developed BCV, another concrete technology that led to significant advancements in structural engineering (Resplendino 2004). In light of these rapid advancements in concrete technology, in order to develop design guidelines for UHPFRC structures and characterize the performance of these materials, recommendations on UHPFRC were issued in France in 2002 (AFGC-Sétra 2002).

Beginning in the 2000s, UHPFRC has been widely applied in many countries, in structures ranging from footbridges to rail bridges and airport runways (Tanka et al. 2013). Despite the increasing adoption of this technology, though, the only comprehensive design guidelines for UHPFRC are the *French Interim Recommendations* mentioned above (AFGC-Sétra 2002). Having said that, more recently the Japan Society of Civil Engineers proposed guidelines for the design and construction of UHPFRC structures (JSCE 2009).Table 1 summarizes the developments of UHPFRC.

This state-of-the-art review aims to provide an overview of the introduction and development of UHPFRC, highlighting the raw materials and mix proportions, as well as its application in bridge engineering, structural retrofitting, and repair. This review will provide insights on the development of UHPFRC and its applications. Finally, the fatigue behavior of UHPFRC will be outlined.

2 RAW MATERIALS OF UHPFRC

2.1 *Components*

The traditional concrete is generally made using Portland cement, coarse aggregate, fine aggregate, and water with or without admixture while UHPC is made by removing coarse aggregate and replaced with fly ash and micro-silica and adding superplasticizers (Xue et al. 2020). Lee et al. (2017) pointed out the role of micro-silica to improve the strength and density of UHPC. Although UHPC is strong in compression, it is very weak in tension. To prevent the tensile crack to propagate, steel fibers with a tensile strength of 200 – 2600 MPa are used in the concrete mix (Aydın&Baradan2013). UHPFRC generally contains cement, silica fume, quartz flour, sand, water, PCE admixture and fibers (Camacho 2013) discussed below.

2.2 *Cement and Silica Fume*

The cement content used in UHPFRC is very high (between 700 and 1100 kg/m^3) in comparison to other special concrete (Wille&Naaman2010). Good mechanical results have been found with reduced C_3A elements and also with so called “oil well elements” (Droll2004). So, Portland cements with a low C_3A content are recommended due to their low water demand.

Table 1. Summary of the developments in UHPFRC from 1970’s to date (Naaman & Wille 2012).

Year	Concrete strength (MPa)	Source/Ref.	Name	Special conditions
1972	230	Yudenfreund et al.		Paste: vacuum mixing; low porosity; small specimens
1972	510	Roy et al.		Paste: high pressure and high heat; small specimens
1981	200	Birchall et al.	MDF (Micro-defect-free)	Paste: addition of polymer; bending strength up to 150 MPa
1981-1983	120 - 250	Bache	DENSIT; COMPRESSIT	Mortar and concrete; normal curing; use of micro silica
1980 all	120 – 250	Bache; Young; Jennings; Aitcin	DSP (Densified small particles)	Improved particle packing, use of micro silica, use of superplasticizers
1987	Up to 140	Bache	CRC (Compact Reinforced Concrete)	High volume of steel fibers with reinforcing bars
1987	Open range	Naaman	HPFRCC (High performance fiber reinforced concrete)	Mortar and concrete with fibers leading to strain hardening response in tension
1991	Open range	Reinhardt & Naaman	HPFRCC (First International Workshop)	Toward reducing the fiber content
1992	Open range	Li and Wu	ECC (Engineered Cementitious Composites)	Mostly mortar with synthetic fibers; strain hardening behavior in tension
1994	In excess of 150	De Lerrard	UHPC	Optimized material with dense particle packing and ultra fine particles
1995	Up to 800	Richard & Cheyrezy	RPC	Paste and Concrete; heat and pressure curing; particle packing
1998 and later	Up to 200	Lafarge	DUCTAL	90^0 C heat curing for 3 days; steel fibers up to 6%
2000 and later	Up to 200	Rossi et al. LCPC	CEMTEC; CEMTEC-multi-scale	Up to 9% fibers, hybrid combinations
Early 2000	Up to 200	Many researchers Worldwide (Graybeal, Rossi)	UHPC and UHP - FRC	Many formulations based on DUCTAL
2005	Up to 140	Karihaloo	CARDIFRC	Optimized particle packing and mixing procedure
2004	Open range >150	Fehling & Schmidt	First International Symposium on UHPC	Many formulations similar to DUCTAL with and without heat curing, with and without fibers
2005	Up to 200	Jungwirth	CERACEM	Formulations similar to DUCTAL, larger fibers, larger aggregates
2008	Open range >150	Fehling & Schmidt	Second International Symposium on UHPC	Many formulations similar to DUCTAL with and without heat curing, with and without fibers
2011	>150	Accorsi & Mayer	UHPC Workshop	First US Workshop
2011	Up to 290	Wille & Naaman	UHP-FRC	No heat curing; optimized packing
2012	Open range > 150	Fehling & Schmidt	Third International Symposium on UHPC	

Silica fume (SF) is a by-product from industrial synthesis of silicon alloys, and it is considered essential for the production of UHPFRC due to its pozzolanic properties. SF reacts with calcium hydroxide and produces more of the CSH binder, which has a much higher strength. When CH is replaced by CSH, the porosity decreases in the bulk resulting a significant increase in strength (Sellevold 2009). Also, to produce UHPFRC, it is very important to achieve maximum packing density, which is achieved successfully due to the usage of silica fume. SF can increase the workability by replacing water in the voids. Since silica fume is far smaller than the cement particles (about 1/100), it is very efficient filler (Sellevold 2009) increasing the packing density. The optimum content of silica fume in UHPFRC is reported as 20% and 30% (Park et al. 2008, Schachinger 2004, Tanaka 2008, Rogeau 2004).

2.3 *Fly Ash (FA) and Quartz Flour*

Fly ash is a by-product from furnaces often from thermoelectric power-plants. Fly ash can be either an aluminosilicate or a calcium silicate. It provides an enhancement of the workability (Ha et al. 2012). Fly ash has a water reducing effect due to spherical shape (Malhotra & Mehta 2002). Quartz flour has same composition as silica sand. Since the surfaces are comparable to the cement (Schachinger et al. 2008), it is sometimes considered as binder in the W/B ratio. It is reported that quartz flour is absolutely inert if the curing is done at 20ºC, but it shows the pozzolanic behavior when curing is done over 150ºC (Schachinger et al. 2008, Reda et al. 1999).

2.4 *Fiber*

Fibers are necessary for increasing the ductility and post-peak behavior in UHPFRC, and to avoid brittle failures and reduce autogenous shrinkage (Empelman et al. 2008, Eppers&Müller2008).It has been seen in the past that fibers increase the tensile and flexural strength, but fiber's contribution to compressive strength in UHPFRC is rather modest. If workability is of importance, a mixture of larger amount of short fibers and smaller amount of long fibers are normally used while long fibers can work on both micro-cracks and macro-cracks when workability is not of importance (Rossi 2001). Following Equation 1 (Hughes &Fattuhi 1976) is used to determine fiber factor.

Fiber Factor = $V_f \ . \ l/d$ (1)

where V_f is the volume fraction, l/d is aspect ratio (l = fiber length, d = diameter of fiber). Table 2 shows the properties of some selected fibers used in the UHPFRC.

Table 2. Typical properties of fibers (Shi et al. 2015).

Type	Diameter (µm)	Young modulus (GPa)	Elongation (%)	Tensile strength (MPa)
Glass	10-16	70-80	2.5-3.5	1400-2500
Wood	25-400	15-40	-	50-1000
Carbon	7-18	200-480	1.2-1.6	1800-4000
Steel	250-1000	200-250	0.5-4.0	280-2800
Asbestos	≤0.5	84-140	0.3-0.6	500-980
Acrylic	5-17	16-23	9-11	800-950
Polyester	10-80	6-18	11-15	735-1200
Polyethylene	800-1000	5-6	3- 4	200-300
Polypropylene	20-70	3.5-11	15-25	300-770
Nylon	23	4.2-5.2	18-20	900-960
PVA	1.30	5-50	6-17	600-2500
Aramid	10-12	60-120	2.1-4.5	2500-3100

2.5 *Superplasticizer*

The use of superplasticizers is very crucial to achieve sufficient workability in UHPFRC due to low w/b ratio, and the development of UHPFRC could not be possible without a suitable superplasticizer. It has been possible to reduce the water content up to 40% by using admixtures used for casting UHPFRC (Camacho 2013), and these admixtures are called polycarboxylate based plasticizers (PCE). Mixing time, setting time and workability can be controlled by changing the molecule of the PCE.

3 MIX PROPORTIONS OF UHPFRC

UHPFRC formulations often consist the materials discussed in Section 2. Different combinations can be used depending upon the job necessity and client's demand. Raw materials are selected in such proportions in mix design so that required strength can be achieved. Table 3 summarizes some mix designs suggested by previous researchers and available commercial products.

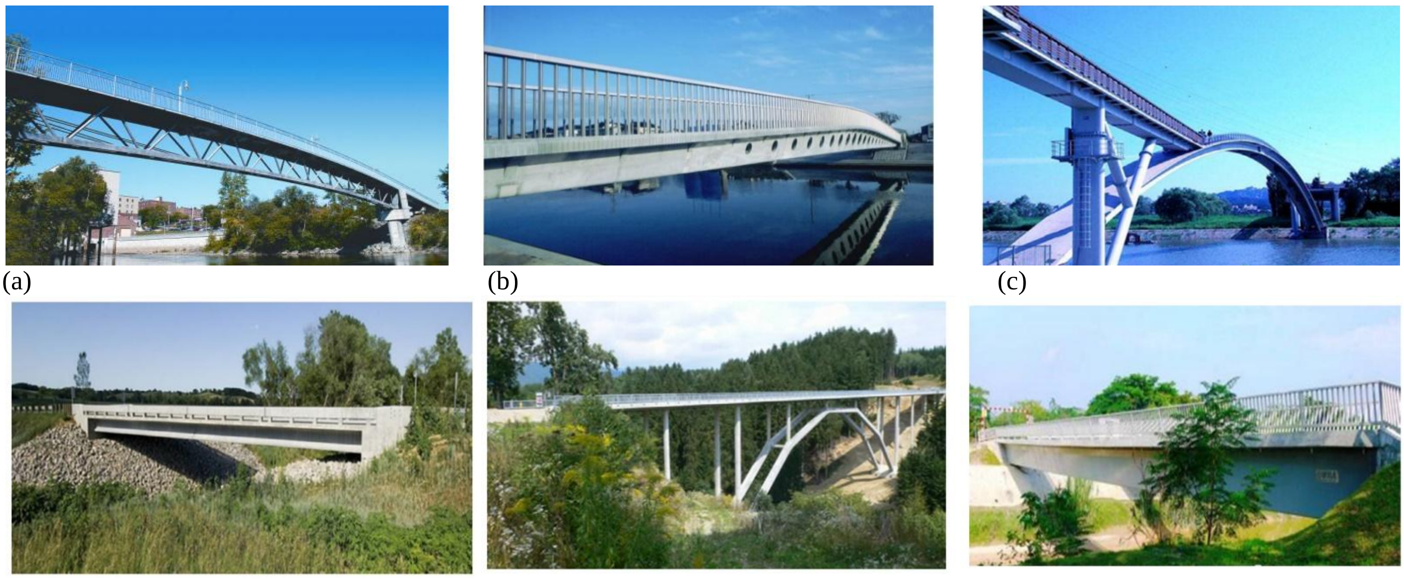
4 APPLICATION OF UHPFRC IN BRIDGES

The first application of UHPFRC was the pedestrian bridge built in 1997 in Sherbrooke, Quebec, Canada. At that time, the local government hoped to use a new type of bridge showing up-to-date achievement in the bridge construction. The deck was made with concrete having compressive strength of 200 MPa. High ductility, low maintenance cost was found due to the use of UHPFRC in this overpass; a truly remarkable event in the history of bridge engineering.

Table 3. Mix proportions of UHPFRC.

Material (kg/m^3)	Ductal®	CEMTEC®	BSI®	Richard & Cheyrezy (1994)	Voort (2008)	Lampropoulos et al. (2016)	Haber et al. (2018)	El-Tawil et al. (2018)
Portland Cement	712	1050	1114	955	610–1080	657	783.5	385
Fine Sand	1020	514	1072	1051	490–1390	1051	-	232.4
Coarse Sand	-	-	-	-	-	-	760	930
Silica Fume	231	268	169	229	50–334	119	305.6	193
Ground Quartz	211	-	-	-	0–410	-	216.5	-
Superplasticizer	30.7	44	40	13	9–71	59	13.5	23
Accelerator	30.0	-	-	-	-	-	-	-
Steel Fibers	156	858	234	191	40–250	236	245.4	156
Water	109	180	209	153	126–261	185	164	156

Sakata – Mirai, a pre-tensioned box girder footbridge, is the first UHPFRC bridge constructed in Japan in 2002. The ratio of girder height to span is 1/90 at the ends of girder (Tanka et al. 2013), and it was initially planned to replace four old concrete bridges. Due to the innovative design using UHPFRC, larger circular openings in the web was achieved.



(a) (b) (c) (d) (e) (f)

Figure 2. a) Pedestrian bridge, Sherbrooke, Quebec, Canada (Source: Lafarge); b) Sakata – Mirai footbridge (Tanaka et al. 2008); c) South Korea Peace Bridge (Source: www.seoul.go.kr.com); d) American Mars Hill Bridge. (Source: www.ductal.com); e) Wild Bridge (Source: Nguyen et al. 2015); f) KampungLinsum Bridge (Source: Vooet al.2012).

South Korea has made remarkable progress in UHPFRC in bridge engineering. The Peace arch bridge, world's first UHPFRC arc bridge, located in South Korea was completed in 2002. The main span of the bridge is 120 m, and the main arch consists of six precast prestressed segments (Zhou et al. 2018). Peace bridge has become an exemplary in the construction of UHPFRC arch bridge.

The Mars Hill Bridge, a single span bridge with three 110 ft. Ductal® girders, located in Wapello county, Iowa, is the first UHPFRC bridge in USA. Because of high ductility and durability, no rebar was used in this bridge. In 2006, this bridge was awarded PCA (Portland Cement Association) Concrete Bridge Award due to innovative features, simple aspect and removing the problems of corrosion in rebar.

Wild bridge, first UHPFRC bridge of Austria, was constructed in 2010. The bridge has nine spans of 15.0 m and two extreme spans of 11.0 m. The construction of Wild Bridge in Austria has shown the benefits of UHPFRC like longer durability, economic efficiency and excellent mechanical performance.

Completed in 2011, Kampung Linsum Bridge is the first UHPFRC bridge of Malaysia over Simin River. There was no shear reinforcement in the girder due to the excellent shear capacity of UHPFRC (Voo et al. 2012). The compressive strength was reported 180 MPa and flexural strength as 30 MPa. The bridge consists of a single span of 50 m. In 2011, the Kampung Linsum Bridge was awarded the Malaysia Book of Records due to its excellent design.

5 APPLICATION OF UHPFRC IN STRUCTURAL RETROFITTING AND REPAIR

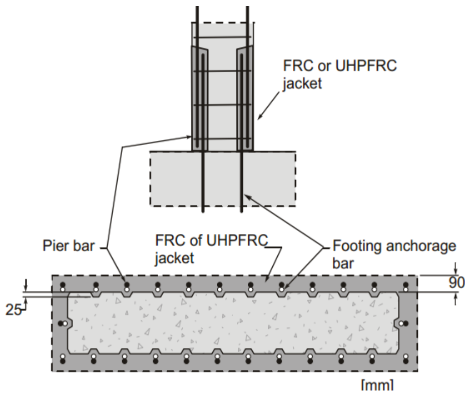
UHPFRC has been increasingly adopted for structural retrofitting (Martin – Sanz et al. 2019) since it is reliable and cost effective compared to the conventional retrofit techniques for bridge component. Moreover, UHPFRC has become an excellent repairing material for the aged structures due to its higher durability, ductility and lower permeability.

5.1 *Seismic Retrofitting of Bridge Piers*

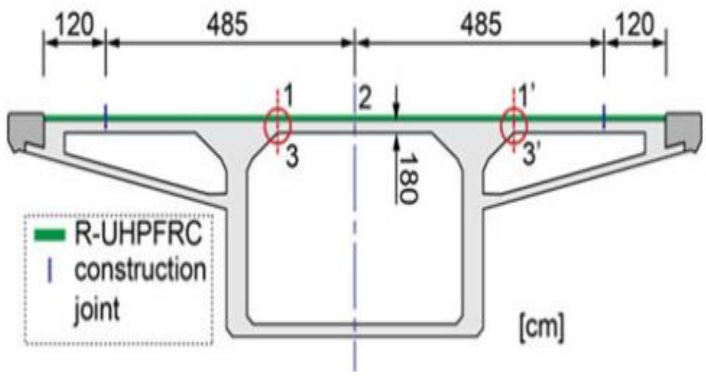
A retrofitting method was developed in Ecole Polytechnique Montreal, Quebec, Canada for bridge piers having lap splice at base. One specimen with poor detailing and another specimen having same cross-section strengthened with UHPFRC jacket were tested under reversed cyclic loading with increasing displacement. The test results showed excellent improvement in the strengthened column, and failure mode changed from brittle to very ductile (Massicotte & Boucher- Proulx 2011). A retrofitting concept was proposed considering that fibers are capable of mitigating the propagation of splitting cracks in concrete cover. The existing concrete cover was replaced by FRC jacket for retrofitting existing columns as shown in Figure 3(a). The anchorage performance of bars was enhanced due to the elimination of splitting failure mode.

5.2 *Strengthening of Decks and Box Girders of Chillon Viaducts*

The Chillon viaducts are located in Switzerland where a layer of R-UHPFRC shown in Figure 3(b) was used to strengthen the slab and box girder (Brühwiler et al. 2015). A layer of R-UHPFRC was used on the bridge deck slab to increase the slab's ultimate bending and shear resistance in transverse direction. Also, waterproofing was achieved with the use of R-UHPFRC to protect the deck slab from water and chloride intrusion. The layer was 50 mm thick, and due to the use of R-UHPFRC, ultimate bending resistance in the hogging moment area of box girder was increased by 20% and shear resistance was increased by 40%. Besides, the UHPFRC layer significantly increased stiffness of the girder.



(a)



(b)

Figure 3.a) UHPFRC jacket (Massicotte & Boucher-Proulx 2011) b) Geometry of the box girder cross section (Brühwiler 2019).

5.3 *Rehabilitation of Buna Bridge*

Buna Bridge, a Croatian riveted steel bridge was decommissioned in 2010 for testing prior to and after rehabilitation by using UHPFRC slab that was connected to steel girders by steel shear studs. The stress reduction of 40% and 20% reduction in deflections were observed. A series of experimental static and dynamic tests were carried out for strengthening and rehabilitating structure, and UHPFRC strengthening technique reduces stresses up to 40% and effective bonding using steel studs were achieved.

5.4 *Improvement of Three Highway Twin Viaducts*

Three highway twin viaducts are located in Central Switzerland having a total length of 1050 m and composed of four slender precast prestressed girder. To increase the load bearing capacity for adopting future traffic demands, the viaducts were strengthened by adding a strong R-UHPFRC layer on the top of slab. The layer was 100 mm thick in hogging moment zone, and in transverse direction, the deck slab in sagging moment region was strengthened by 45 mm thick UHPFRC layer with rebars, and an increase in torsional stiffness was observed.

5.5 *UHPFRC in Connections between Bridge Precast Deck Elements*

Use of precast deck is increasing in industry due to lesser construction time, but the connection between precast elements used in bridges is one of the crucial part since poor joints will lead to water and chemical-agent infiltration (Verger-Leboeuf et al. 2017). Researchers have pointed out that connections made with UHPFRC can increase shear and bending capacities of precast deck elements (Graybeal 2010, Perry et al. 2012, Sritharan et al. 2012). The excellent mechanical performance of UHPFRC provides some advantages over traditional connection method since small width joints can be used with UHPFRC to develop full capacity in bridge decks (Graybeal 2010). It is well understood that restraint shrinkage is one of the drawbacks of the connection inducing cracks that can be prevented by using UHPFRC due to its very high tensile strength and impermeability. It was recommended to use FRC precast decks with UHPFRC connections from the research work of Verger-Leboeuf et al. (2017). As a result, construction time will be significantly reduced with a durable deck.

6 FATIGUE BEHAVIOR OF UHPFRC

Fatigue is one of the most detrimental actions for bridge deck due to increased traffic demands. It is significant to understand the fatigue behavior of bridge deck strengthened with UHPFRC. When UHPFRC is used as strengthening material on top of the RC bridge deck slab, tensile fatigue stress is developed on the overlay due to fatigue loading. Since UHPFRC has significantly higher tensile strength than normal and high strength concrete, its use in the structural members those are subjected to tensile stress can be an effective solution. Figure 4 shows a typical tensile stress-strain curve of UHPFRC.

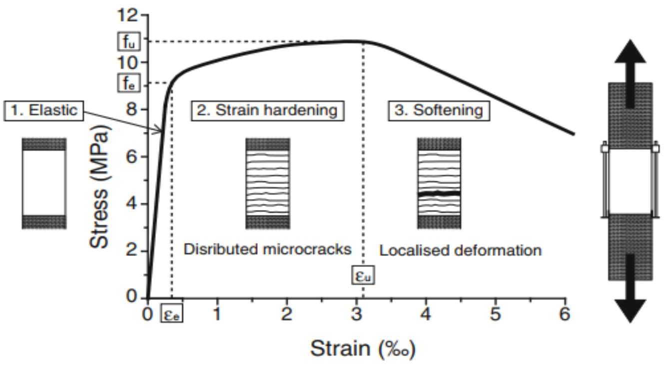


Figure 4. Schematic representation of tensile stress-strain curve of UHPFRC (Makita & Brühwiler 2013).

Three domains can be observed during tensile testing of UHPFRC: elastic domain, strain hardening domain and strain softening domain. In the strain hardening domain, more and more micro cracks develop in the specimen and macro cracks with larger width become visible in strain softening domain. The tensile fatigue behavior was investigated by Makita & Brühwiler (2013) to determine endurance limit of UHPFRC, and endurance limit was found to exist in all three domains with S-ratios ranging from 0.70 to 0.45 (S is the ratio of the maximum fatigue stress to elastic limit strength).

7 CONCLUSIONS

This paper reviewed the state-of-the-art on the material properties and applications of UHPFRC in bridge engineering with structural retrofitting, repair and fatigue behavior. Based on the review and discussion above, it can be summarized as follows:

- The main characteristics of UHPFRC are its high compressive strength, high tensile strength, high durability, reduced porosity, improved microstructure, and lower associated maintenance cost compared to the conventional concrete.
- UHPFRC has gained popularity in the rehabilitation and repair of bridge components, as it increases the ultimate load and stiffness, and reduces the crack width of the member. Furthermore, UHPFRC has been found to be an excellent alternative for use in longitudinal and transverse connections between precast bridge deck elements, as it increases the shear and bending capacities of the precast deck component.
- The use of fibers helps to overcome the shortcomings associated with conventional concrete by preventing the propagation of tensile cracks, and thus increasing the ductility.
- The use of UHPFRC to strength structural components in terms of fatigue behavior has been shown to be an effective strategy since it increases the tensile strength, and thereby prevents or delay the propagation of tensile cracks.
- Reviewing the applications of UHPFRC in bridge projects, it stands as a promising prospect in bridge construction in Bangladesh.

Most of the previous studies on UHPFRC have been conducted on strengthening of bridge decks. Strengthening of other bridge components such as bridge piers, girders, connections should also be investigated. Also, there is a need for investigations on the fatigue behavior of structural members strengthened with UHPFRC.

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