Utilisation of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) for Retrofiting – a Review

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Abstract. Retrofitting has become a proven method for improving the load carrying capacity of existing concrete structural elements subjected to high mechanical loading, ageing or aggressive environments. Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a relatively new generation of cement-based retrofitting material with a very high compressive strength and low permeability attributed to its tightly packed microstructure, also displaying excellent bonding ability with normal structural concrete. It has the potential to eliminate various problems caused by other retrofitting methods like FRPs or externally bonded steel plates as a result of the mismatch of stiffness with parent concrete. This study presents an overview of UHPFRC focusing on its properties, design, applications and challenges. The performance of UHPFRC concrete mix is greatly influenced by the type and degree of packing of its constituents in the cementitious matrix, necessitating the need for optimisation. Strength properties are very much higher when compared to that of conventional concrete alongside with increased durability aspects. The retrofitting technique showed an enhancement in the load carrying capacity of deteriorated structures. Therefore, UHPFRC can be considered as a practical solution to improve the sustainability of buildings and other infrastructural components. However, as a retrofit, there are some concerns regarding the loss of ductility. This broadens the need for methods to improve its ductility. This paper presents the state-of-art review of existing literature that deals with the retrofitting/rehabilitation of structures using UHPFRC. Altogether, the paper aims to expand the awareness regarding UHPFRC which was otherwise hindered, owing to limited design codes.

1. Introduction

A well-developed infrastructure reflects the growth and economic prosperity of a country. Most of the old reinforced concrete structures have undergone severe deteriorations over ages. This requisites the development of new, cost-effective strengthening and retrofitting strategies to extend the service life of these structures with a lower frequency of repair interventions. Growing demands in the construction industry necessitates materials of higher strength and durability properties. Some of the commonly available schemes of retrofitting include external prestressing, steel or concrete jacketing, fibre reinforced polymers (FRPs), near-surface mounting etc. Although these techniques are highly effective, certain drawbacks such as increase in dead load in case of concrete jacketing, corrosion of steel plates, debonding, long term durability, fire sensitivity and ageing of adhesion materials in case of FRPs are observed [1,2].

Over the past two decades an advanced cement-based material with improved strength and durability characteristics, namely, Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is gaining interest worldwide. It defines a unique combination of low permeability, high strength and toughness.
2. UHPFRC
UHPFRC refers to a fiber reinforced superplasticised concrete, wherein coarse aggregates are replaced with very fine sand and highly active pozzolanic material. When compared to high performance concrete, ultra-high performance concrete has 2-3 times greater compressive strength (more than 150 MPa) and 2-6 times higher flexural strength [3]. It typically consists of cement, binders like GGBS, silica fume, quartz powder, fine sand, high range water reducing admixtures, fibers and low amount of water. UHPFRC combines the properties of self-compacting concrete, fiber reinforced concrete and high performance concrete as depicted in figure 1. Enhanced microstructure can be attained as a result of higher particle packing density, very low water content and proper mixing procedure [4]. This enables it to have extremely low permeability requiring less cover. Appropriate amount of well distributed fibers eliminates brittleness and enhances the mechanical properties.

![Figure 1. Different types of special concrete [5].](image)

2.1. Development of UHPFRC
Immense research has been conducted over the past decades in the field of concrete technology to attain higher compressive strength. During 1980s, superplasticisers (SP) were introduced to reduce the water/binder (w/b) ratio up to 0.3. High dosage of silica fume and SP, further reduced the w/b ratio to 0.16. With optimal grain size distribution, compressive strength up to 280 MPa was achieved with reduction in porosity and enhancement of durability. These technological breakthroughs along with application of low porous materials led to the development of ultra-high performance materials. With the addition of steel fibers in the late 1980s, ductility of the matrix improved. Compact Reinforced Concrete (CRC) and Slurry Infiltrated Fiber Concrete (SIFCON) are two examples of this type.

In 1990s Richard et al. [6] developed Reactive Powder Concrete (RPC) with improved fineness and compressive strength in the range of 200-800 MPa. Ductal® was the first commercial UHPC developed through the RPC technology in the late 1990s. However, high production costs limited the use of this material [7]. Much progress was achieved in the 21st century with the introduction of UHPFRC [5,8]. To reduce the cement content, supplementary cementitious materials were used as substitutes. Furthermore, standard water curing in place of temperature curing was also reported [1,9-15]. The applications of ultra-high performance concrete are gaining ground as a result of emergence of cost-effective and environment-friendly UHPC.

2.2. Typical mix of UHPFRC
Optimum particle packing density and matrix homogeneity are the key factors determining the characteristics of UHPFRC. Hence, appropriate selection of raw materials plays an important role in mixture design of this cementitious composite in order to achieve good workability and strength. Basic principles identified by various researchers [16-19] in designing UHPC include (i) reducing w/b ratio and including a wide range of material classes reducing the matrix porosity, (ii) eliminating coarse aggregates thereby improving homogeneity, and (iii) incorporating steel fibers to improve ductility.

Various particle packing models have been reported for the mix design of UHPC. First one of these types was Linear Packing Density Model (LPDM) (1986) formulated by Larrard and Sedran [20]. But its linear nature failed to address the relations between packing density and material proportions. Further improvement led to Solid Suspension Model (SSM) (1994) and Compressible Packing Model (CPM)
(1999) based on virtual packing density and compaction index [21]. Aashay et al. [9] have successfully developed an economical UHPC based on CPM. Continuous models like Fuller Thompson model (1907) and Andreassen model (1930) assume presence of all possible particle sizes in the distribution system [21]. Yu et al. [15] used the modified Andreassen and Anderson model (1997) to develop UHPFRC with much lower binder content of 650 kg/m$^3$. This model recognised finite size of materials considering minimum particle size in distribution. Besides empirical methods, statistical methods based on neural networks were also adopted. Ghafari et al. [22] found the optimum contents of silica fume and cement to be 9% and 24% by volume of concrete respectively.

A typical UHPFRC mix contains Portland cement, fine sand, quartz powder, steel fibers, superplasticiser and water. The $w/b$ ratio typically lies between 0.16-0.20 [23,24]. Supplementary cementitious materials and fillers like fly ash, GGBS, rice husk ash may be incorporated as a substitute to reduce large high cement contents. A GGBS replacement level up to 40% was found to be effective without sacrificing the strength properties [10].

Table 1. Typical mix components of UHPFRC [16].

| Component     | Weight range (kg/m$^3$) |
|---------------|------------------------|
| Cement        | 610-1080               |
| Fine sand     | 490-1390               |
| Silica fume   | 50-334                 |
| Crushed quartz| 0-410                  |
| Fibers        | 40-250                 |
| Superplasticiser | 9-71              |
| Water         | 126-261                |

2.3. Properties of UHPFRC

2.3.1. Workability. The relative slump flow ability linearly decreased with the addition of steel fibers as a result of high cohesive forces [15]. To have sufficient flow it is necessary to add sufficient quantity of high range water reducers into the mix, up to 5% mass of cement [23,24]. Improved workability can be achieved with the use of air-entraining agents as well as by appropriate incorporation of fillers to replace cement. Flow capacity is greatly influenced by the packing density of inclusions [25].

2.3.2. Compressive strength. Compressive strength increased with increase in fiber volume up to 3%, along with delayed crack propagation [13,14]. Main factors influencing compressive strength included the fiber content, curing conditions, loading rate and mix components. Elevated temperature cured specimens were found to have improved strength of 10-30% when compared to standard water cured specimens [1,11,26,27]. However, the lowered performance with standard water curing could be nearly compensated by increasing the fiber volume. Supplementary materials like silica fume and filler materials increased the strength as a result of pozzolanic action and intimate matrix packing [13,28-29].

2.3.3. Tensile and flexural strength. Tensile strength depends largely on the type, amount and orientation of fibers in the matrix. UHPFRC exhibits significantly higher strength compared to other cementitious materials as shown in figure 2. Studies have demonstrated a proportional increase in flexural and tensile strength in steel fiber ratios up to 3% in weight [2]. Tensile strength ranges from 7 to 15 MPa.

2.3.4. Durability. Low w/b ratio and enhanced microstructure have resulted in low porosity and permeability, resistance to medium erosion and better wear resistance. Micro-cracks may develop due to high rate of autogenous shrinkage[23]. However, UHPC has been found superior to conventional concrete in terms of wear resistance, carbonisation depth and chloride ion permeability [2,30,31]. Mixture design based on modified Andreassen model resulted in UHPCs with lower and comparable porosities [15].
3. UHPFRC for retrofitting applications

The excellent performance of UHPFRC offers various applications in the field of building constructions, infrastructural strengthening and precast technology. Indeed, it is already being commercialised in many countries like Australia, Germany, France, New Zealand, etc. The first application of UHPC overlay was reported on a bridge over La Morge River, Switzerland [33]. One another example includes the retrofit of containment walls of a nuclear reactor in France [34].

3.1. Advantages over existing methods

One main concern for selection of a repair material is to have its mechanical properties close to that of its substrate. Most of the popular techniques of retrofitting using fiber-reinforced plastic laminates or externally bonded steel plates can result in brittle failure of the retrofitted structure due to the mismatch of tensile strength and stiffness [35,36]. Delamination failure of FRPs may limit the effective utilisation of the retrofitting material [37]. Higher tensile strength of these materials may possibly make the sections over-reinforced, thereby demanding alternate materials like UHPFRC of comparable strength parameters. Being a cement-based retrofitting material UHPFRC exhibits better compatibility and bonding ability with concrete. Prefabrication of strengthening strips can bring about standards in quality and the total cost might be much lower when compared to many other methods of strengthening [1]. Moreover, it can foster speedy construction with minimal interventions [38].

3.2. UHPFRC – NC bond strength

Studies reported a 40% increase in bond strength of UHPC overlay when compared to normal strength concrete. Wet surface displayed higher bonding than dry surface [39]. Specimens jacketed using sandblasting technique performed better under combined shear and compression [3,40]. Epoxy bonded specimens exhibited better performance in peeling tension attributed to its higher tensile strength when compared to Normal Concrete (NC) and UHPFRC. In essence, the UHPFRC-NC bond quality is excellent regardless of surface preparation [3,41].

3.3. Flexural strengthening

Flexural strength of UHPC could be 2-6 times greater than High Performance Concrete (HPC) [42]. Addition of UHPFRC layer to the tension side of beams showed improved stiffness, increased load carrying capacity and delayed flexure and shear crack propagation. The strengthened beams behaved monolithically [3,12,43,44]. However, beams strengthened on its three faces as in figure 3 displayed high capacity with significant loss in ductility when compared to the former configuration [11,43,45]. UHPFRC retrofitted beam-column joints also exhibited increased load carrying capacity, ductility and energy dissipation characteristics. Additional confinement lowered the rate of stiffness degradation which is significant in structures subjected to seismic loading [37,46].

Epoxy bonded prefabricated UHPFRC strips on the tension side increased the cracking load when compared to jacketed specimens due to the high tensile strength of epoxy [3,35]. The strips along with the parent beam behaved as an integral unit with no de-lamination[14,47]. Original load carrying...
capacity was regained after strengthening even in beams subjected to 90% preloading [47]. The bending performance of laminates was found to improve with the addition of reinforcing bars into the laminate increasing the ultimate load carrying capacity by 35% [14]. Shrinkage strain was found to reduce with the addition of steel fibers [11]. Different bonding techniques were employed for attaching the precast strips on to the concrete surface, viz., anchoring and epoxy gluing. The glued specimens showed a 5% increase in ultimate load carrying capacity than anchored ones [14]. Provision of anchorages further reduced the effective area, thereby weakening the UHPFRC layer [1]. UHPC strengthening in slabs increased the overall stiffness and excellent energy absorption capacity resulting in a ductile flexural failure. However, not much improvement in ultimate strength was noticed [43].

3.4. Shear strengthening
Alaee et al. [45], conducted study using short strips adhered onto the tensile and vertical faces of beam specimens along with long continuous strips near to the support region. Flexural mode of failure was noticed with increased load carrying capacities. Punching shear capacity increased around 70% when UHPC was provided within the critical punching shear area of RC slabs [43,48]. Retrofitting of seismically deficit beam-column joints enhanced the shear capacity and stiffness characteristics. Prefabricated strips showed sufficient increase in strength compared to jacketing technique. However, the strength degradation using strips was observed to be 30% higher than jacketed members as a result of delamination [46]. Diagonal tension shear strength and ductility under lateral loading in an RC shear wall were found to increase due to the confinement provided by UHPFRC jacket [49].

3.5. Torsional strengthening
Limited works have been carried out in the field of torsional strengthening using UHPFRC. Torsional capacity and cracking strength was found to improve in retrofitted beam members. A minimum increase of 65% in side wrapped specimens and a maximum of 260% in fully wrapped specimens were achieved proving the effectiveness of using UHPFRC in torsional strengthening [50].

3.6. Limitations and future recommendations
Preparation of UHPC with comparable performance under strict quality control and limited design guidelines restricts its widespread usage. Application method and type of retrofitting was found to influence the behaviour and ultimate strength of the parent member [14]. The peak load and ultimate displacement of epoxy bonded specimens were 15–20% lower when compared to jacketed specimens [3]. Embedding of reinforcing bars in the laminate finally resulted in sudden delamination of UHPFRC strips from the substrate surface [14]. Research can be extended to investigate retrofitting RC members using hybrid FRP wrapping along with strengthening strips. Although the stiffness is improved, 25–30% reduction in ductility was noticed in strengthened members when compared to unstrengthened members [35,47]. Enhancement in ductility in case of prefabricated strips by incorporating different strip configurations could be studied. Further, efforts to reduce carbon footprint by exploiting alternate raw material replacement combinations in UHPC mix could be carried out.

4. Conclusions
Matrix homogeneity and improved packing density make UHPC an excellent material with higher durability aspects and mechanical properties. Incorporation of suitable quantity of supplementary
cementitious materials could sufficiently lower the high cement content in UHPFRC. Elevated temperature curing improves the mechanical properties when compared to standard water curing. Being a cement based retrofitting material, UHPFRC displays outstanding bond quality with parent concrete. As a retrofit, UHPFRC effectively complemented the flexural and shear strength of RC members. However, there are some issues regarding the loss of ductility and strength degradation. If the above limitations are rectified, UHPFRC proves to be a promising solution to significantly improve the durability and structural reliability of deteriorated concrete structures.

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