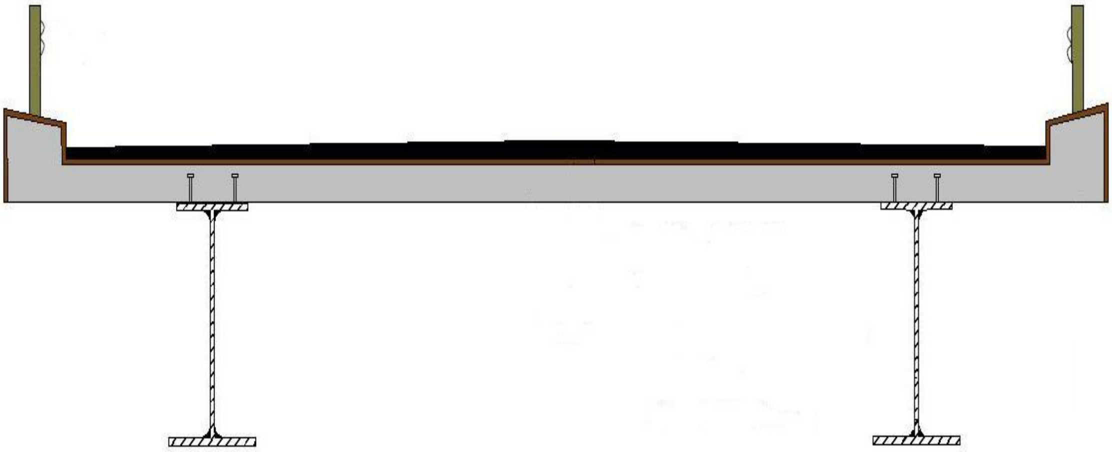

Development of more robust bridge deck slabs

Potentials of Ultra High Performance Fiber Reinforce Concrete)

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

FAHEEM AHMAD KHAN FARIDOON
SOHAIB NAZAR

Department of Civil and Environmental Engineering
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Concrete Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011
Master's Thesis 2011:72

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Cover:
Proposed cross section of the composite bridge deck with NSC prefabricated Slab and UHPFRC Overlay, section 8.2.1, page 70 of the report

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ABSTRACT

Parts of the bridges in Sweden and other countries have shown to have a too low resistance with respect to deterioration. This leads to costly repair interventions that disturbs the traffic and results in high Life Cycle Costs (LCC) for the bridges. This is the case for the bridge deck slabs with connecting elements, such as edge beams, railings, expansion joints, sealing and pavement. The aim of this master thesis is to investigate the problems in bridge deck slabs, suggest possible solutions to these problems and in particular, find the potentials of Ultra High Performance Fiber Reinforced (UHPFRC) Concrete for these problems.

Bridge deck slabs and their connecting elements deteriorate faster than the other parts of the bridge due to traffic loads and use of de-icing salts during winter. The various mechanisms of the deterioration that take place in bridge deck slabs are corrosion of reinforcement, cracking, spalling, delamination and potholes. A state-of-the-art description has been presented including suggestions to possible solutions to these problems, such as cathodic protection and galvanizing of the steel reinforcement, use of corrosion inhibitors, use of fiber reinforced concrete and polymers, and bridges with integral abutments.

This investigation primarily focuses on the mechanical behaviour, durability and rheological properties and application of UHPFRC to develop more robust bridge deck slabs. UHPFRC shows better performance at post-cracking due to the strain hardening behaviour with distributed micro-cracks, enhancing the service life of bridge deck slabs.

An inventory of two bridges in Sweden has been used as case studies to investigate and illustrate the possibility to use UHPFRC in their construction and rehabilitation. UHPFRC is an almost impermeable and highly ductile material; however, being relatively expensive, it has been only suggested to be used as overlay, for bridge deck slab and edge beams for rehabilitation as well as new construction. It has also been suggested that UHPFRC should be used in joints for connecting precast elements, giving a continuous bridge deck with narrower (smaller/ thinner) and stronger joints.

Key words: Bridge deck slabs, UHPFRC, Robust, Life Cycle Cost, Interventions, Strain hardening

Contents

Preface

This master thesis was carried out at Chalmers University of Technology, at the department of Civil and Environmental Engineering, Division of Structural Engineering, Concrete Structures, in Göteborg, Sweden. The work is a part of a larger cooperation project between the Swedish technical universities (Chalmers, KTH, LTU and LTH) and the Swedish Transport Administration.

At first, we are most grateful to our supervisor and examiner Assistant Professor Mario Plos for his guidance, support, encouragement and valuable feedback. We could not have done this without his help and appreciation. He read our report and discussed it with us with great interest. It was our great pleasure to work under his guidance.

We are also very thankful to our friends who have always supported us. Furthermore, a special gratitude to our present and former teachers, for helping us to reach to this stage.

Finally, thanks to our Parents, who bestowed their love upon us, took care of us, helped and guided us, and supported us in every single moment of our life.

Göteborg June 2011

Faheem Ahmed Khan Faridoon

Sohaib Nazar Awan

Notations

Roman lower case letters

f_{cd}	Design value of concrete compressive strength
f_{ck}	Characteristic compressive cylinder strength of concrete at 28 days
E_{cm}	Mean elastic modulus of Concrete
f_{ctm}	Mean tensile strength of concrete
G_f	Fracture Energy of Concrete
k_w	Water Permeability
f_{yk}	Tensile Strength of Steel reinforcement

Greek lower case letters

ϵ	Strain
v	Poisson ratio
α	Co-efficient of thermal expansion
σ	Stress
σ-ω	Stress-crack opening
α_{cc}	Coefficient for long term effects on compressive strength
γ_C	partial safety factor for concrete

Abbreviations

UHPFRC	Ultra High Performance fiber Reinforced Concrete
FRC	Fiber Reinforced Concrete
HPC	High Performance Concrete
NSC	Normal strength Concrete
LCC	Life Cycle Cost
CRC	Compact Reinforced Composite
ARCHES	Assessment and Rehabilitation of Central European Highway structures
SAMARAIS	Sustainable and Advanced Materials for Road Infrastructure
FRP	Fiber Reinforced Polymer
FE	Finite Element
NYSDOT	New York State Department of Transportation
CP	Cathodic Protection
BCV	Beton Composite Vicat
RPC	Reactive Powder Concrete
ASR	Alkali Silica Reaction
EPFL	Ecole Polytechnique Federale de Lausanne
LCPC	Laboratoire Central Des Ponts Et Chaussees
CTE	Co-efficient of Thermal Expansion
ASTM	American Standard for Testing Materials
AASHTO	American Association for State Highways and Transport Officials
AFGC	Association Francaise de Genie Civil
SETRA	Service D'etudes Techniques des Routes et Autoroutes

1 Introduction

Roads are the major prerequisite for transportation and connection for mankind. For smooth flow of transport, a highway is intended to adopt the shortest possible route with comfortable and acceptable profile. The highway needs to pass valleys, mountains, deserts and rivers. Many factors intersect the intentional profile of the highway, where water, other roads and railways are the most frequent ones. Therefore, bridges are constructed along the route of the highway for crossing of these hinders with the intention to connect the different parts of the highway. Hence, bridges are a key factor to make the aim of the highways achievable.

Bridges are designed by qualified and experienced bridge engineers, keeping in view safety, economy, aesthetics and environmental considerations together with production and maintenance aspects. There are different conceptual and detailed design methods available following different design codes. Each design code has the intension to support the design to achieve the vital goals of the bridge. Quality assurance is the first priority during the design and construction process in order to guaranty a good life time performance of the bridge. However, with the passage of time deterioration and degradation occurs in the bridge, which eventually requires maintenance, repair and rehabilitation. Investigation has been done to improve the design methods to ensure safety throughout the life time of the structure and reduce the maintenance cost.

1.1 Background

Parts of the bridges in Sweden and other countries have shown to have a too low resistance with respect to deterioration. This leads to costly repair interventions that disturbs the traffic and results in high life cycle costs (LCC) for the bridges. The parts that have shown a too low resistance are typically those that are particularly exposed to traffic, weather and environmental impact. This is the case for the bridge deck slabs with connecting elements, such as edge beams, railings, expansion joints, sealing and pavement.

The Swedish Transport Administration has the ambition to improve the performance of the bridge deck slabs to reduce the resources spent on maintenance and repair and to reduce the carbon dioxide emissions. A joint pre-study is currently being performed by the Swedish technical universities (Chalmers, KTH, LTU and LTH) and CBI (Swedish cement and concrete research institute) for the Swedish Transport Administration to identify weaknesses and development potentials of concrete bridge deck slabs with connecting elements, and to suggest further research. The master thesis is intended to support and complement this pre-study.

1.2 Purpose

The purpose of this master's thesis was to perform a literature study and a state-of-the-art description of concrete bridge deck slabs with connecting elements. The focus was on parts and functions that show a too low resistance and on possible solutions to the identified problems. Furthermore, the aim was to make an in-depth study of one of the possible solutions to the identified problems.

1.3 Aims and objectives

The overall aim of the work was to contribute to the improvement of the life cycle performance of bridge deck slabs in order to reduce the resources spent on repair and maintenance and to reduce the carbon dioxide emissions associated with this.

The objectives of this study were therefore:

- To identify weaknesses and development potentials of concrete bridge deck slabs, including connecting elements such as edge beams, railings, expansion joints, sealing, pavement and drainage systems.
- To study the potential of existing interventions and give suggestions for further development.
- To do in-depth study on the possibility to improve the strength and structural stability by using ultra high performance fiber reinforced concrete (UHPFRC).
- To suggest an economical way to apply UHPFRC for rehabilitation and for construction of more robust bridge deck slabs.

1.4 Method and Scope

The study was mainly performed as a literature study. Based on the literature study, alternative design solutions for more robust deck slabs were proposed for two existing bridges, and compared to original design solutions.

The literature study was initially focussed on the current design methods and design practise of bridge decks. Then these design methods and design practise were critically reviewed to gather information about the weaknesses in the bridge deck slab and connecting elements. Thereafter investigations were done to find possible solutions to overcome these weaknesses and to judge the potentials of the suggested solutions. Applications of different methods to improve the resistance of bridge deck slabs against deterioration were studied.

One of the most promising solutions was to use Ultra High Performance Fiber Reinforced Concrete (UHPFRC). An in-depth study was done on the properties of UHPFRC in the development of more robust bridge deck slabs. Furthermore, previous experiences of application of UHPFRC for bridges in the world were studied.

Finally, two case studies were performed. In the first case study, the use of UHPFRC for rehabilitation of existing bridges was theoretically applied on a bridge deck slab. An existing bridge with insufficient durability for the deck slab and deteriorated edge beams was chosen as a reference bridge. In second case study, a comparison was done between an industrially produced bridge alternative and a reference composite bridge, conventionally produced with a cast in-situ normal strength concrete bridge deck slab. The new alternative bridge solution considered of main steel girders and prefabricated normal strength bridge deck elements joined and covered with UHPFRC.

2 Design of Bridge Deck Slabs

2.1 General

The design procedures used today were originally created by research and development, and proved to be adequate and applicable by experience. Initially, a preliminary survey of the construction site and highway is carried out for the conceptual design of a bridge. During this stage, data is collected about the profile and alignment of the highway, topography of the area, soil properties, current of the flow of water, wind, snow and ice formation and projected traffic volume. This leads to the decision of the shape and type of bridge, length and number of spans, type of abutments and foundation, and load on the structure.

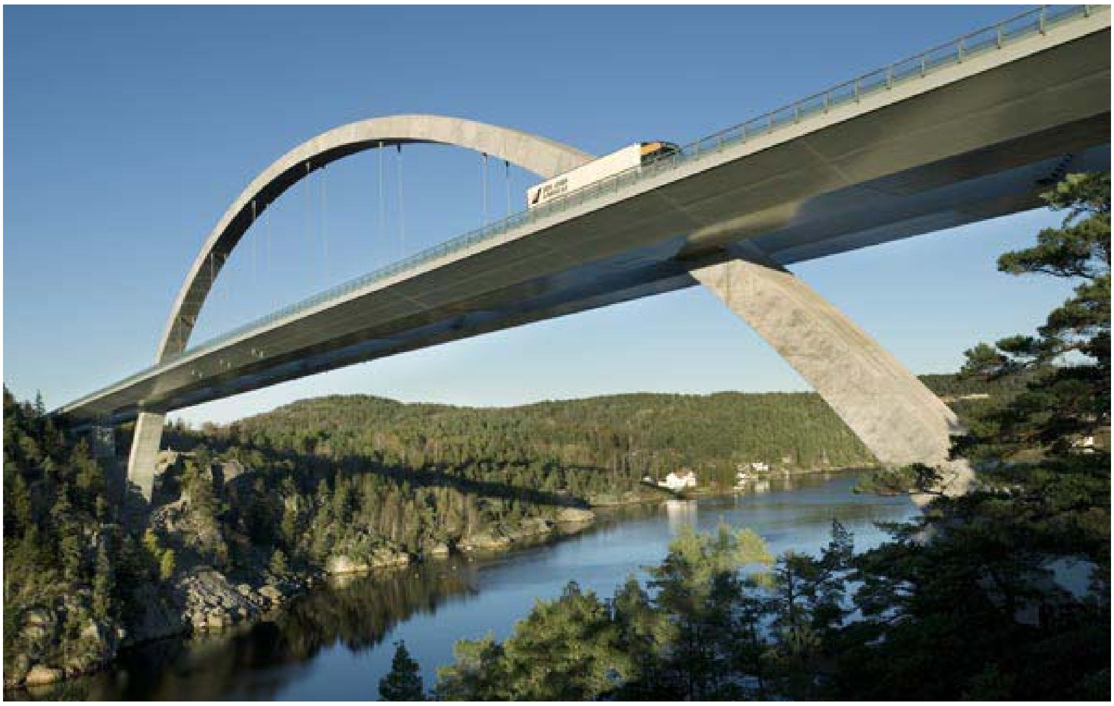

Figure 2.1 Svinesund Bridge between Sweden and Norway. Adopted form (trafikverket, 2007).

Thereafter, the bridge designer develops the detailed structural design such as drawings and dimensions of the structure considering connection details, drainage from the bridge, lightning, sealing and surface coating, water proofing, sidewalks and railings.

The structural system of a bridge can often be described in terms of the longitudinal and transverse load carrying structures. The longitudinal structural system of a bridge may be designed for, for example, beam, frame, arch, cable stayed, or suspension action. The transverse structural system normally consists of a bridge deck slab with connecting elements such as edge beams, railings, parapets, drainage system, sealing, asphalt layer and expansion joints. For longer bridges it transfers the traffic loads to the main (longitudinal) load carrying system. For short bridges the deck transfers the loads to the supports directly (Ryall *et al.* 2000).

For larger spans, from approximately 25 m, prestressed concrete bridges have shown great result. Since concrete is strong in compression but weak in tension, pre-stressing leads to better performance in serviceability limit state with no or less cracking and smaller deflection. In ultimate limit state, more or higher quality reinforcement may result in higher capacity but the prestressing itself has only a minor influence on the capacity. Prestressing gives a very free choice to the bridge engineer while deciding the shape and length of bridge. Prestressing is an advanced system of construction of concrete bridges with good serviceability performance. The designer decides about the dimensions of the structure and reinforcement according to the ultimate limit state analysis in flexure, torsion, shear and punching shear, and for crack widths in the serviceability limit states (Ryall *et al.* 2000).

Steel was earlier the favourite material for long span bridges because of its high strength. However, the technique of prestressing has to a great extent replaced the steel as bridge material. A main reason is that concrete requires less maintenance cost particularly with respect to corrosion compared to pure steel bridges. However, steel is commonly used for the main girders in medium and long span composite bridges with concrete decks and substructures. The combination of prefabricated prestressed girders with cast-in-situ deck is a widely used construction method for bridges in many parts of the world (Raju, 2007).

The deck is a vital part of the bridge and functions as a pathway for all types of traffic. It is directly exposed to all environmental conditions occurring in the area of location of the bridge throughout the year. Therefore, it should be strong and durable enough to withstand chemical and mechanical effects of rain water, de-icing salt, friction between the tires and deck surface, and the traffic load. The deck consists typically of a slab, edge beams, sealing, road pavement, expansion joints, drainage system, railings and lightning as shown in the Figure 2.2.

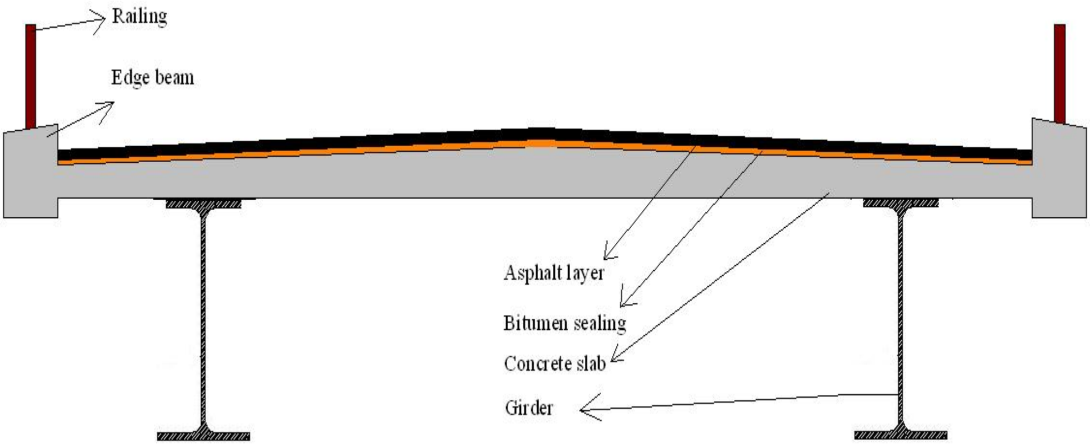

Figure 2.2 Typical section of a bridge superstructure.

2.2 Reinforced concrete bridge deck slabs

Reinforced concrete is the most widely used construction material for bridges. Cast-in-situ reinforced concrete bridges are simple to construct. It gives good results when the span of the bridge is less than 25 m. However, for the bridges having longer span, the dead weight becomes larger (Ryall *et al.* 2000).

There are different materials used for the construction of the bridge deck slabs, of which concrete and steel are the most prominent and widely used throughout the world. However, steel has proved to be an expensive material to use for bridge deck slab construction and concrete is the dominant material. Other types of construction materials for bridge deck slabs are stress-laminated timber and Fiber Reinforced Polymer (FRP). The main advantage of using these materials for the construction of bridge deck is that they together with orthotropic-steel decks form very light weight bridge decks. Consequently, especially orthotropic steel is used for the construction of longer bridges to control the weight problem. The bridge deck is most commonly constructed of reinforced concrete because of the in-situ workability and the good ability to distribute the loads. Reinforced concrete is most cost-effective for slab structures because it distributes the concentrated loads in two directions (Domone & Illston, 2010).

A concrete bridge deck slab is designed for serviceability limit state and ultimate limit state. The design differs depending on the specific geometrical, environmental and traffic conditions. In the world, there are two codes widely used for the design of bridge deck slabs today: AASHTO-LRFD, (AASHTO, 2010) and Eurocode 2-Part 2, (CEN, 2004). For the bridge decks different type of cross sections are used depending on the acting load, span of the bridge, construction material and aesthetics. The most common type of deck slabs used in Sweden is solid slabs but ribbed and voided slabs do also occur.

2.2.1 Solid slabs

This is the simplest type of bridge deck slab used for short span bridges. Solid slab bridges are efficient in distributing the concentrated loads. These are one way or two way spanning. Mostly solid slab bridge is simply supported. The solid slab can be constructed monolithic or non-monolithic with the abutment (Ryall *et al.* 2000).

2.2.2 Voided slab

Above a span of about 10m, the dead weight of a solid slab bridge becomes excessive. Hence, the use of voids inside the deck slab gives a positive result by reducing the weight of the slab. The provided void diameter is not more than 60% of the slab thickness. Polystyrene void formers are used in circular shapes. Transverse reinforcement is provided in the flanges. Flexural and shear design is done longitudinally as well as transversely for the section. Mostly these are precast structures requires minimum formwork thus accelerating the speed of construction (Ryall *et al.* 2000).

However, the trend of voided slab is not yet adopted in Sweden due to problems with the quality in production of these slabs. Furthermore, it is difficult to inspect these voids for regular maintenance activities.

2.2.3 Ribbed slab

Here, the slab has several longitudinal ribs or beams, cast together with the slab. Transverse beams are provided over the supports. The load distribution is relatively poor, hence, transverse beams can be provided at the middle of span to avoid sagging (Ryall *et al.* 2000).

2.3 Edge beams

Edge beam is that part of the bridge deck which is situated along the side of the deck slab. According to ACI 318-05, it is used for the distribution and transmission of the traffic loads close to edges of the bridge deck slab. It accommodates the railings and lighting poles and also directs the rain water to flow through the drainage system, protecting the underside of bridge deck see figure 2.3. In case of cable stayed bridges the cables are accommodated on edge beams, thus, here the edge beam is used as the main load carrying system. Concrete is used as construction material for edge beams. The connection between the deck slab and the edge beam is made through transverse reinforcement. The transverse reinforcement from the deck slab is embedded in the edge beams. Monolithic construction is stressed to avoid any leakage risk through joints.

Figure 2.3. Edge beam supporting railing and lighting pole

2.4 Expansion joints

The function of joints in a bridge deck slab is to accommodate movements in the concrete slab due to temperature change, shrinkage, settlements and restraining forces due to pre-stressing. Expansion joints are common at the end of the bridge deck slab, at the abutments, but may also be used to allow independent deformations of different parts of a bridge deck for long bridges. Joints must be designed to allow smooth flow of traffic, safety for pedestrians and bikers, lowest possible noise from the traffic flow and to have enough strength to support the traffic load. They should resist leakage of de-icing salt water and other environmental affects. There are different kind of materials used for these joints such as asphalt, rubber, plastic, steel, epoxy and some other chemical materials. Joints are designed in numerous shapes and sizes depending upon the function for allowable movement impact (Chen *et al.* 2000).

Expansion joints are designed for serviceable limit state as well as ultimate limit state to ensure durability throughout the lifetime of bridge. There are three basic types of joints designed according to the accommodated movement. Small movement joints accommodate motion up to 45 mm, medium from 45 mm to 130 mm and large from 130 mm onwards (Chen *et al.* 2000).

The bridge deck slab can be constructed monolithic or non-monolithic with the abutment Non-monolithic section shows a lower resistance to deterioration due to leakage of drainage water and wear and tear in the expansion joints which affects the pier and sub-structure abruptly. Maintenance and repair cost is much higher as it is cumbersome to work on the sub-structure (Ryall *et al.* 2000).

Therefore, monolithic structures are commonly preferred for short and normal span bridges to avoid the problem of deterioration of sub-structure. Furthermore, integration of the bridge deck slab with the abutments reduces the sagging moments in the mid-span of the slab (Ryall *et al.* 2000).

2.5 Railings

Railings are protections provided at the edges of the bridge deck slab to save the vehicle, in case of collision or accident, from falling down from the bridge. Railings are also provided to separate the bicycle and pedestrians pathways from the main vehicular lanes. Therefore, railings should be strong enough to accommodate the impact from a vehicle at the time of an accident. At the same time, the railings should be deformable and should absorb energy in order to minimize the impact on drivers and passengers in case of an accident. Generally, steel, wood, plastic and reinforced concrete are used as material of construction for railings. The choice of material and type of railings depend upon the traffic volume and type of traffic. AASHTO recommends crash test to determine the type of railings to be used (Chen *et al.* 2000). Also In Europe and Sweden, Crash tests are performed to determine the quality of railings to be used. Steel is the most dominant material used for railings in Sweden due to its strength, deformability and good performance in case of accidents.

2.6 Carriageway drainage

Water and substances suspended in water is the major enemy of the concrete structures. Water can appear in the form of snow, rain and ice during the life time of a bridge. In particular, the de-icing salts, when mixed with water, can seriously affect the concrete bridge deck slab. Penetration of saline water into concrete structures can cause corrosion of steel bars and freeze-thaw deterioration. The carriageway drainage system reduces the possibility of standing water on the bridge deck surface and allows a smooth flow of water away from the bridge. The water from the drainage system should not affect the sub structure and foundation. While designing and constructing the bridge deck slab, attention should be given to the drainage system. Different types of drainage elements are installed in the deck of the bridge depending on the function and necessity (Ryall *et al.* 2000). In Sweden, there are two types of drainage systems in bridge decks. One is external drainage system and the other is internal drainage system. The rain water drops directly on the asphalt layer on the bridge deck. The deck slab is sloped towards the edges to direct the water towards the edge beam. Pipes are installed at different locations between the deck slab and edge beams for carrying this rain water from the deck to the reservoir. However, some amount of water penetrates from the asphalt layer inside the deck slab. To drain this water, pipes of small sizes are installed at different locations to drain off this water to the reservoir.

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2.7 Sealing

Sealers are used on concrete bridge deck slabs to increase the durability and service life of the structure, thus reducing the life cycle cost. Sealers are used as moisture protection on concrete bridge deck slabs by preventing the slab from contact with polluted water. In this way, corrosion of steel bars can be avoided to a considerable level (Ryall *et al.* 2000).

A variety of sealers are used depending on the density of concrete and type of environment. Most of them are organic in nature such as penetrating sealers, polymer coatings and bituminous sealers (Ryall *et al.* 2000).

Penetrating sealers are products which are absorbed on the surface of concrete forming a water repelling surface. It allows water vapours to pass because there are pores and cracks in concrete which help in the drying process (Ryall *et al.* 2000).

Polymer coatings are products which forms a film or a membrane on the surface of concrete structure, and which does not allow water to penetrate into the concrete structure. It does not allow water vapour to pass (Ryall *et al.* 2000).

Bituminous sealers are products which are used as a water repelling membrane between the concrete bridge deck slab and the asphalt surface (Ryall *et al.* 2000).

2.8 Pavements

The layer of asphalt is spread on the top of the sealing in order to protect the concrete slab from mechanical abrasion and to provide a smooth surface for the traffic. The asphalt layer is usually bituminous concrete which consists of bitumen mixed with sand and coarse aggregates. This is also called wearing course. This layer forms the top surface of the bridge deck slab. Sometimes liquid bitumen is also spread on the top of this wearing layer. The pavement is designed to obtain the required friction between the tires and the wearing course. Typical Swedish bridge deck slabs with sealing and pavement have been shown in the Figure 2.4 (a) and Figure 2.4 (b).

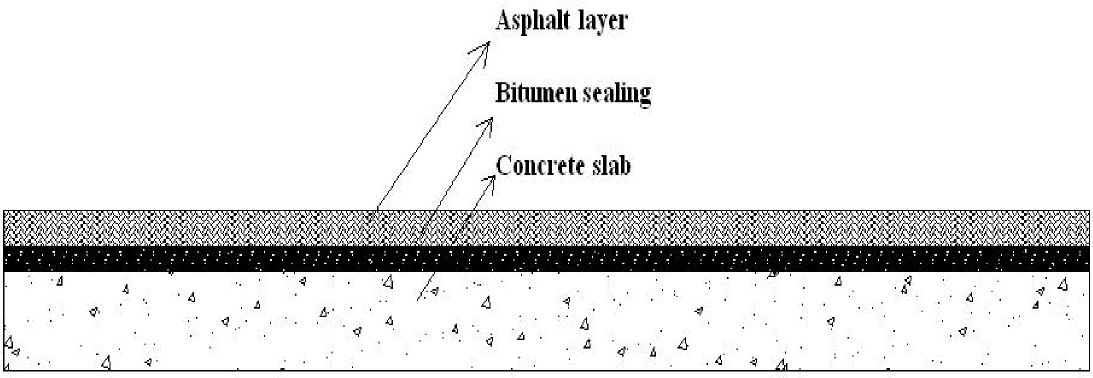


Figure 2.4 (a) Example of composition of a Bridge deck slab with sealing and pavement.

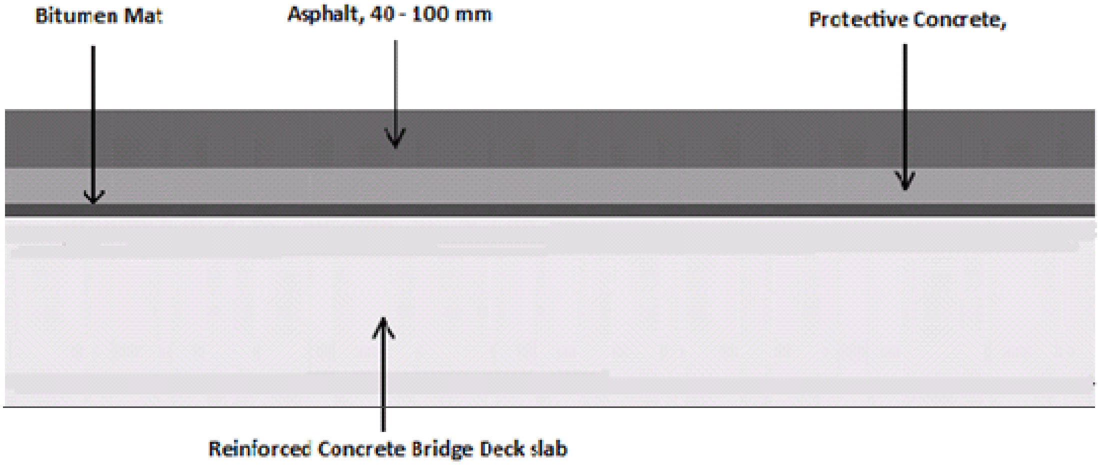


Figure 2.4 (b) Example of composition of a bridge deck slab with protective concrete and pavement (Adapted from Paulsson 1999).

3 Weaknesses in Concrete Bridge Decks

Bridge decks are constantly subjected to concentrated traffic loads and are exposed to environment actions. Consequently, they deteriorate faster than other parts of the bridge. Also during winter, de-icing salts are used to keep the roads free from ice and they are spread over the bridge decks. De-icing salts, which are generally a mixture of sodium chloride and calcium chloride penetrate into the concrete and cause deterioration of the concrete structure and in particular, the steel reinforcement (Frangopol *et al*, 2003).

Deck accessories exhibit various types of damages and these damages can be of different importance e.g. damages to the connection between edge beam and slab, expansion joints, water proving membranes, pavement and elements of drainage system are most dangerous (Radomski, 2002).

3.1 Deterioration of bridge deck slabs

The deterioration in the bridge deck slab is mainly due to poor material quality (poor mix, curing conditions), poor weather conditions (freeze and thaw cycles), use of de-icing salts and increasing traffic loads. The various mechanisms of the deterioration that take place in bridge deck slab are cracking and spalling, abrasion, delamination and potholes (Frangopol *et al*, 2003).

3.1.1 Cracking

Concrete cracks in fresh as well as in hardened state. Cracks makes it easier for chlorides to penetrate into the concrete and cause corrosion of steel reinforcement The most common causes of cracking in bridge deck slabs are shrinkage stresses, temperature changes, corrosion of steel reinforcement, chemical reactions in the concrete (alkali-aggregate reaction) and mechanical loading causing flexure and shear cracks (Radomski, 2002).

Cracking that occur before hardening are mostly caused by plastic shrinkage and plastic settlement of the concrete mix. Due to extreme weather conditions the evaporation rate of water may increase while the concrete is still in a plastic state, causing surface to shrink more than the interior concrete and resulting in surface cracks (Yazdani & Kleinhans, 2008). Furthermore, poor mix design can cause excessive bleeding of the mix leading to plastic settlement. Also movement of formwork in the fresh state of the concrete can induce cracking (Sustainable bridges, 2007).

Extreme weather conditions at the time of casting and heat produced during hydration induces thermal stresses in concrete. Restraint to these thermal stresses can cause cracking of concrete. Bridge decks may exhibit a high degree of restrain due to composite action of the deck and supporting girders if they are not cast at the same time. Due to the hydration reaction during casting the temperature of the concrete deck slab increases. If the temperature of the girder remains unchanged, thermal stresses are developed in longitudinal direction. To relieve these stresses the deck will crack in transverse direction, perpendicular to the stress direction. Thermal stresses also develop in the concrete due to temperature gradient through the thickness of deck, regardless of restraint. This difference in gradient may produce non uniform strain (Brown *et al*. 2001). Furthermore, restraint to shrinkage stresses also cause cracking in the deck. This is a problem when edge beams or parts of a bridge deck are replaced for existing bridges. Furthermore, the restraint caused by the steel girders when casting the concrete deck may cause shrinkage cracks for composite bridges.

Poor structural detailing may also cause cracking. Simply supported spans allow free rotation at supports, therefore thermal and shrinkage stresses are uniform along the length of the span. However, continuous spans provide rotation restraints at the inner supports which may cause cracking over the interior supports if the provisions for restraints are not provided in the design. The transverse cracking is influenced by the thickness of deck, reinforcement spacing and concrete strength (Brown *et al*. 2001). Due to dead loads, flexure cracks may appear in fresh concrete in areas of negative moment. However, live loads also induce flexure cracks during service life (Yazdani & Kleinhans, 2008).

Furthermore, chemical reactions in the concrete e.g. Alkali-silica reaction, frost damage and corrosion of steel reinforcement also induce cracks in hardened concrete (Domone & IIIston, 2010).

Figure 3.1. Cracks in bridge deck slab

Alkali Silica Reaction

The problem occurs when high alkaline cement is used with reactive aggregate. Alkalies can also be contributed from admixtures and de-icing salts. In the presence of moisture, internal reaction takes place, causing disintegration of the concrete matrix.

When Alkalies in cement reacts with silica, a gel is formed which destroys the bond between the alkalies and cement paste. It is soft but absorbs large quantities of water and expands which results in cracking of concrete. This reaction is called as Alkali-Silica Reaction (ASR). Due to continued supply of water the cracks become larger and extend in width. When expansion of cracks reaches to the surface either pop-outs form or map cracking occurs on the concrete surface as shown in Figure 3.2 (Domone & IIIston, 2010).

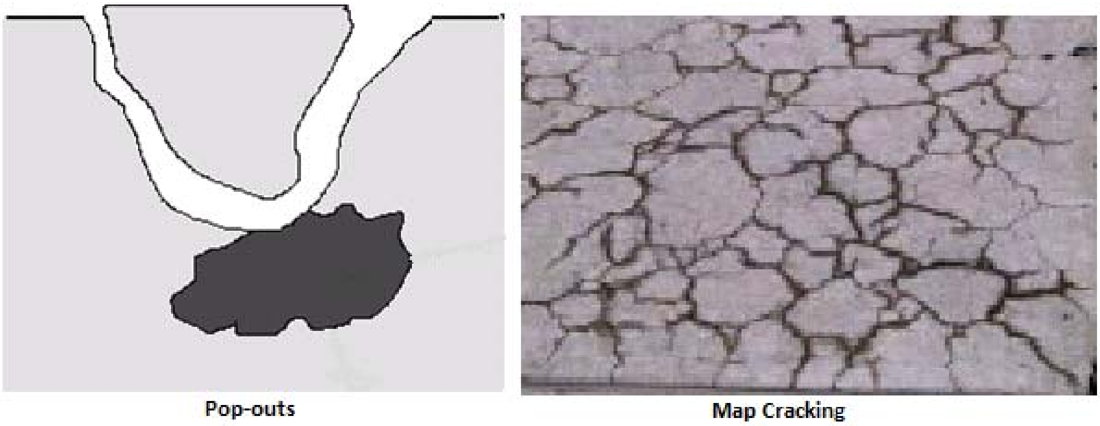


Figure 3.2 Cracking pattern due to Alkali- Silica reaction. Adapted from Domone & IIIston (2010)

Frost damage

Frost damage is a major cause of damage of concrete structures in cold areas. When free water inside the concrete pores freezes in winter, it expands. If there is no free space to accommodate this expansion the internal pressure leads to cracking of the concrete. Successive cycles of freezing and thawing lead to progressive cracking which leads to two types of damages. The first type is the internal freezing of the moisture inside the concrete which cause cracking and reduction of the strength and stiffness of the concrete. The second is the freezing of salt water in contact with the concrete surface, leading to surface scaling of the concrete. It also causes spalling of the damaged part of the concrete. The magnitude of internal pressure depends on the degree of saturation and the porosity of the concrete. One recommendation to prevent frost damage is the use of high strength concrete. Another common way to avoid frost damage is to increase the air content in the concrete mix (Domone & IIIston, 2010) (Hanjari, 2010).

Corrosion

A survey among European railway authorities showed that the major maintenance problem for concrete bridges are corrosion of reinforcement leading to spalling of concrete (Sustainable bridges, 2007). Since road bridges are even more exposed to de-icing salts, it can be expected that the problem is more severe here.

Corrosion is the disintegration of steel reinforcement due to its electrochemical reaction with the surrounding. Corrosion of reinforcement causes two major types of damages in bridge deck slabs. Firstly, the section of the reinforcement decreases which leads to reduction in capacity. Secondly, the corrosion products, the rust, occupy a larger volume than the steel it originates from. As a result splitting forces are induced in the concrete which affects the concrete section in two ways; it destroys the bond between concrete and reinforcement and it will eventually cause spalling of the concrete cover reducing the capacity of section (Sustainable bridges, 2007).

There are three different types of corrosion of reinforcement in concrete bridges. The first type is uniform corrosion in which the reinforcement is equally corroded along and around its surface. It reduces the strength of the bond and eventually causes spalling of concrete (Sustainable bridges, 2007).

In second type, the reinforcement corrodes locally at some points on its surface. A high concentration of chlorides leads to pitting corrosion. This corrosion may lead to reduction of the corroded section of the reinforcement. The third type of corrosion occurs due to a combination of aggressive environmental actions and high stress concentrations, causing rupture failure of the reinforcement. In non-prestressed concrete bridges pitting or uniform corrosion is most common, while stress-corrosion mostly occurs in prestressed concrete bridges (Sustainable bridges, 2007).

Carbonation and chloride ingress are the major causes of corrosion of steel in concrete. Carbonation through the concrete cover causes mainly uniform corrosion of the reinforcement. It is due to reaction between carbon dioxide from the atmosphere and alkaline hydroxide in concrete. Alkalies in concrete pores form a passive layer of protective oxide on the steel surface which stops corrosion. During carbonation all the locally available calcium hydroxide will react and precipitate calcium carbonate, which results in lowering of pH, depassivation of the protective layer and finally the corrosion of steel will start. Corrosion due to carbonation mostly occurs in structures with low concrete cover and in concrete that has high permeability (Broomfield, 1997) (Sustainable bridges, 2007).

Chlorides ingress from the concrete cover mainly leads to pitting corrosion of the reinforcement. The area of reinforcement decreases at the pits. The chlorine itself is not used in the chemical reaction but it acts as a catalyst and helps in destroying the passive protective layer. Corrosion due to chloride ingress is usually a problem in coastal areas or in colder regions where high amount of de-icing salts are used in winter (Broomfield, 1997) (Sustainable bridges, 2007).

The total time to concrete cracking due to corrosion consist of two stages. In the first stage carbon dioxide and chlorides will take time to reach the steel; this can be considered as safe service life. The residual service life, in which corrosion takes place, continues until the limit state is reached and cracking and spalling of concrete way appear during this stage; see Figure 3.3 (Domone & IIIston, 2010).

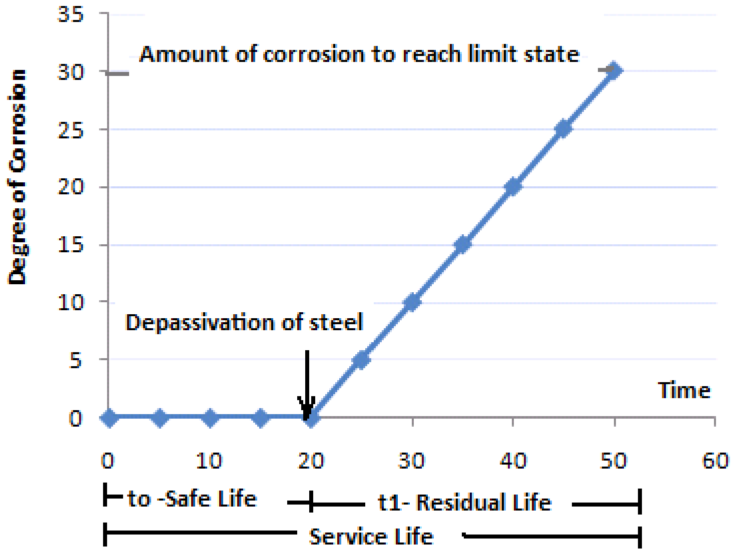


Figure 3.3 Service life model of reinforced concrete exposed to a corrosive environment. Adapted from Domone & IIlston (2010)

Different exposure classes apply when corrosion is induced by chlorides from road de-icing salts (Domone & IIlston, 2010).

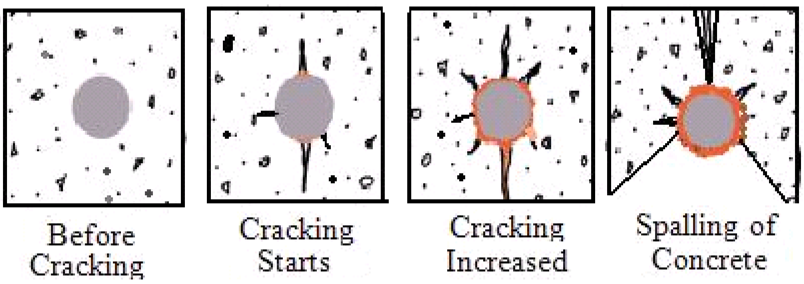


Figure 3.4 The corrosion of steel bar starts causing the expansion steel bar and cracking in concrete. As the times passes, the more extensive cracking leads to spalling of concrete. Adapted from Domone & IIlston (2010)

3.1.2 Abrasion

Abrasion is the phenomenon of scratching and rubbing away of top surface of the pavement. Wear and rutting are two general forms of abrasion. Rutting is most common in overlays with asphaltic wear course. While wear and tear is mostly common in concrete overlays. It is mostly caused by the studded tires and blades of snow ploughs. Due to abrasion the pavement becomes slippery and thickness of the overlays also reduces (Yazdani & Kleinhans, 2008) (Paulsson 1999).

3.1.3 Delamination

Due to low bond between old and new materials, separation along the contact plane occurs, called delamination. In decks with overlays, delamination is one of the most common types of deterioration. Delamination is a major problem in particular between the concrete and sealing of the membrane (Frangopol *et al*. 2003).

3.1.4 Potholes

Due to cracks in the overlays of deck, water seeps inside these cracks. When the water freezes during winter it expands and pushes the part of the overlay closest to the road surface away which leads to formation of potholes on the surface. The potholes can be irregular in shape, have different depth and have sharp edges. Potholes are usually formed in heavy traffic lanes (Frangopol *et al*. 2003).

Figure 3.5 Pothole formed on the bridge deck slab

3.2 Damages to edge beam

Edge beam distributes and transmits the traffic loads close to the edge of the bridge deck slab. It also supports rails and lighting towers. Cracking of edge beam occurs due to the factors explained in section 3.1.1, see figure 3.6. Furthermore, corrosion of lighting poles and railings also cause damage to the edge beams. The figure below shows the cracked edge beams of Stallbacka Bridge which were replaced in August 2010.

Figure 3.6 Cracks in Edge beam

3.3 Damages to expansion joints

The primary function of bridge deck joint is to accommodate contraction and expansion. Damages to expansion joints cause inconvenience to riding quality. Usually expansion joints have shorter life time than other parts of the bridge deck. According to (Radomski, 2002) the most common types of damages to expansion joints can be classified as follows.

- The seal of expansion joints may get cracks and split. Due to damaged sealing water may go inside the joints which can damage the reinforced part of the deck.
- When a new overlay is added with no regards to the joints, the joint function is impaired. This may also cause transverse cracking in the overlay.
- The Steel parts of the expansion joints may get damaged due to aggressive and extreme environmental changes e.g. corrosion may induce cracking and loosening of steel plates
- Millions of cycles are generated by the traffic load therefore steel parts of the expansion joints may also get damaged due to fatigue.
- If the drainage system is improper, the function of joints is impaired by corrosion of steel parts of joints.
- Insufficient access to the joints for maintenance may lead to the impaired function. As a result, service life of the joints decreases.
- Debris on the surface of bridge decks may accumulate in expansion joints which may prevent free movement of the joints, consequently causing failure of the joints.
- The improper leveling of parts of expansion joints, the joints may get damage to provide smooth riding surface.

Figure 3.7 Damaged expansion joint

3.4 Damages to railings and parapets

Damage to railings, balustrade and parapet do not directly influence the structural behavior of the bridge deck. Railings and parapet are made of different types of materials. Therefore, damages to these elements depend on construction material. Most severe damage is due impact forces caused by the collision of cars. Other damages are cracking of concrete parapet and corrosion of steel railing (Radomski, 2002).

3.5 Damages to drainage system

The efficiency of the drainage system is a major factor influencing the durability of the bridge deck. Therefore, water on the deck due to rain and snow is required to be drained off as soon as possible. Effectiveness of the drainage system depends on the working condition of all elements of the system, such as pipes, gutters, inlets and troughs, etc. The most typical types of damages to drainage system can be classified as follows (Radomski, 2002).

- The accumulation of debris and other contamination cause the choking of inlets and rain water pipes. In addition, in cold regions pipes may get blocked due to accumulation of snow and ice.
- The drainage system may get damage due to corrosion of the steel elements.
- Water leakage through the inlets may cause severe damage to the bridge deck slab.
- When water is not properly drained off due to in sufficient gradient of pavement; this may cause deterioration of the deck.
- Insufficient gradient of the pipes of drainage system also leads to impairment of the drainage system.
- Drainage system may get damage due to mechanical damage to elements of system.

- The drainage system needs regular maintenance; lack of accessibility for maintenance leads to the impaired function and damage of the drainage system.

3.6 Damages to sealing

Sealing are used as water proving in bridge decks to reduce the permeability of concrete and to stop the chloride ingress, thereby increasing the service life of deck. Damage to sealing can be classified as follows.

- Blister or bubble formation may leads to impaired function of the sealing.
- Delamination from concrete underlay may damage the sealing.
- Bad connections to expansion joints and drainage installations may also damage the sealing.
- The sealing may get damage at the connection between slab and edge beam.
- Deterioration of overlays may damage the sealing.

3.7 Damages to pavement/overlay

The overlay provides protection to the deck against deterioration and ensures the riding quality. Thus it reduces the maintenance cost of the bridge. The overlay is exposed to environmental changes, aggressive fluids such as chlorides, carbon dioxide, de-icing salts and also the traffic load. Failure of the overlay leads to following forms of deterioration which reduces the service life of bridge structure.

4 Possible Solutions

Durability of bridge deck slabs is of major concern due to the high repair and maintenance cost. Practices should be adopted to ensure safety, security and serviceability throughout the service life. Research and development is a continuing process for the construction of more robust and durable structures.

Here, some of the key issues regarding deterioration of bridge deck slabs have been addressed such as cracking control and corrosion control.

The bridge deck is directly exposed to environmental actions such as de-icing salt, acid rains and marine environment. Thus the reinforcement is more vulnerable to attack of chlorides due to penetration of chloride ions. Corrosion of embedded reinforcement plays a critical role in limiting the service life of reinforced concrete decks and for the high maintenance costs. Therefore, there is desire of systems which show better performance under severe environmental conditions and that can be rapidly repaired. Increased concrete cover, low permeable concrete, resisting admixtures in concrete and coating on reinforcement bars is used to control the process of penetration of chloride ions, hence protecting the oxide film on the surface of reinforcement bars. In addition, a good drainage system is inevitable for the long term serviceability to avoid accumulation of water on the bridge deck. Furthermore, joints should be properly constructed and sealed to avoid leakage of water. An increase in the resistance against water intrusion into the deck slab can be achieved by using a good water proofing membrane between the concrete slab and the asphaltic layer. Following are the methods used to reduce the risk of corrosion and increase the strength of concrete against cracking.

4.1 Cathodic protection of steel reinforcement

Corrosion is an electrochemical process that requires oxygen, water and steel for chemical reactions. However, corrosion can be stopped if the access to oxygen is controlled. Design concrete practices, sealers and membranes mostly have been used to provide protection. These techniques limit the risk of corrosion to occur, but they cannot control or stop the corrosion process itself.

Cathodic protection (CP) has shown to be an effective way of reducing or eliminating corrosion of steel reinforcement. Galvanic systems and impressed current from an external source are two commonly used CP systems (Yehia & Host, 2010).

In galvanic systems, a more electronegative metal is connected to the steel to be protected. This metal acts as an anode with tendency to lose electrons. Therefore, an electric current is created between the anode and the cathode i.e. the reinforcement steel due to difference in electro negativity (Yehia & Host, 2010).

An alternative is to imply impressed current from an external power supply. A supplementary anode is then connected to reinforcement in the structure. When this anode is connected to the external power source, the steel inside the structure turns into cathode. As long as the steel remains cathode, the rate of corrosion is very low (Clemeña & Jackson 2000).

Conductive concrete is a recent innovation and is now being used as a matrix for CP systems. Conductive concrete is a cementitious admixture having high electric conductivity. It is cast as overlay on bridge and acts as anode. The steel reinforcement in the structure acts as cathode (Yehia & Host, 2010).

4.2 Protective coating of reinforcement bars

Another method of protection from corrosion is to apply a protective coating on the surface of the reinforcement. Epoxy coating of reinforcement is the most common method used. Epoxies form a protecting and resilient film around the reinforcement and shows resistance to water, chlorides and chemicals. The coating can be damaged by mechanical abrasion, so special care and practice is required during handling and fabrication. Galvanizing of the steel is another method used for protection of reinforcement. It is achieved by coating the steel reinforcement with zinc. A tough alloy layer is formed on the steel which makes it easy to handle. A lot of research has been done and it has shown that no coating system can give guarantee for a long time of complete avoidance of corrosion of steel reinforcement in concrete. Use of stainless steel reinforcements can also reduce the risk corrosion. But Stainless steel may increase the initial cost (Yeoman, 1993).

4.3 Use of corrosion inhibitors

The use of inhibitor is another viable solution of stopping and reducing the corrosion of steel in concrete. There are two types of corrosion inhibitors. First type is Integral inhibitors which are mixed with other concrete ingredients to prevent corrosion in new construction. While second category is migrating inhibitors, which are used as treatment for existing concrete structures. Calcium nitrite is most common type of integral corrosion inhibitor. A very thin layer around the steel is formed in concrete by inhibitors, which prevents the corrosion. (Broomfield. 1997) (Bone, 2004).

Migrating inhibitors are only applied to the concrete surface. These inhibitors are used to reduce the effect of corrosion in existing concrete structures. Researchers are still unable to find the long term effectiveness of these inhibitors. The other disadvantages are material cost and difficulty lies in application (Broomfield. 1997) (Bone, 2004).

4.4 Fiber Reinforced Polymers (FRP) composites

Fiber reinforce polymer (FRP) composites have been considered for replacement of reinforcement in bridge deck slabs. Entire bridge decks can also be made of FRP composites. FRP is a new class of composite materials made of high strength fibers and resins. The fibers are typically composed of glass or carbon bounded together by a resin matrix (Benmokrane *et al.,* 2004).

The properties of FRP vary depending on the types of fibers, fiber content, fiber orientation, fabrication process and processing conditions (Park *et al*., 2007). FRP composites are light weight, more durable, less corrosive, have high tensile strength and have low maintenance costs compared to conventional concrete which also make it ideal for rehabilitation. Many bridges in USA have been built using FRP reinforcement. Four bridges were constructed using FRP reinforcement and were tested under sever conditions. These bridges were found more durable in aggressive environment and have shown more competitive performance as compared to concrete bridges reinforced with steel (Benmokrane *et al., 200*4).

Another alternative is to make a whole deck of FRP composites. The two most common deck types used are pultruded profiles (tubular profiles) glued together or sandwich core systems. The specific deck systems are built in factories and transported to the site and glued together by adhesives. If the deck is supported by beams, composite action can be developed by cutting cavities through the deck elements to access the shear studs on the beams and then grouting these cavities. Special attention is required for joining the different parts of the FRP deck together. In experiments, FRP decks have shown very low skid resistance, good corrosion resistance and rapid installation. Epoxy or polymer modified concrete overlays provide better solution to overcome skidding effects (Sams. 2005). The major drawback is that FRP decks are initially more expensive than the decks reinforced with conventional steel and concrete.

4.5 Fiber Reinforced Concrete (FRC)

Another alternative of constructing corrosion-free bridge deck is to use fiber reinforced concrete to construct deck slabs of fiber reinforced concrete. In general, large amount of conventional steel reinforcement are needed to achieve small crack widths. As a result, larger structure dimensions are required. Also pouring of concrete becomes more difficult in case of tightly placed reinforcement. By using fiber reinforced concrete with or without ordinary steel reinforcements reduces these drawbacks. Fibers enhance the post-critical strength of concrete in terms of ductility and reduce the crack widths as shown in Figure 4.1. Fibers also reduce shrinkage in fresh concrete. The typical types of fibers used are steel fibers, glass fibers, natural fibers and synthetic fibers (e.g. polypropylene).

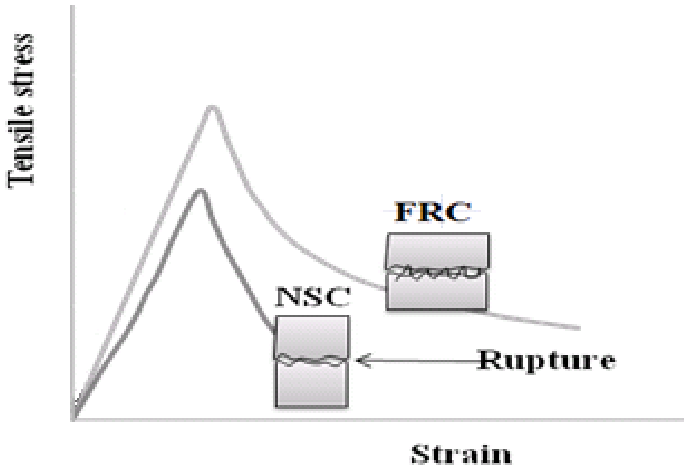


Figure 4.1 Tensile behavior of Fiber reinforced and normal strength concrete

In the beginning, some experiments using polypropylene fibers did not stop the corrosion of steel reinforcement. Therefore, some decks have been designed without steel reinforcement. External steel straps are provided at the bottom of such decks and are made to have composite action with superstructure through the shear connectors. Shear connectors are generally welded to steel beams. While in concrete beams extended shear stirrups act as shear connectors.

The FRC deck gains its strength from the internal compressive arching action between girders is provided by the in-plane lateral restraint. This arching action is achieved longitudinally by the restraint provided by the composite action of stiff girders and in transverse direction, external steel straps provide the restraint as shown in the Figure 4.2. Use of FRC increases the flexural, impact and fatigue strength of concrete. FRC construction cost is about 6% more than the conventional construction; however FRC increases the service life by delaying the localization of cracks and resisting the corrosion. Hence FRC minimizes the long term cost (Mufti *et al.*, 2002) (Coughlin T., 2004).

FRC overlays with glass, metallic and plastic fibers are viable solution for the surface problems. Experiments showed that this type of reinforcement stops the crack growth originating from the overlays and leads to improve long term spalling resistance (Folliard *et al.*, 2006).

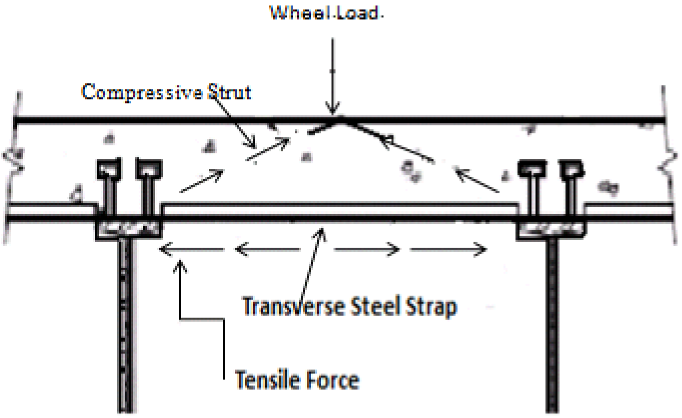


Figure 4.2 Internal Arching Action of FRC Deck. Adapted from Coughlin (2004)

4.6 Integral abutment bridges as a possible solutions for damages with expansion joints

Expansion joint is a common part of the bridge deck slab which allows the relative movement between different parts of the bridge deck slab. However, the lifespan of the expansion joint is significantly lower than the lifespan of the bridge deck slab. Damaged expansion joints cause leakage of water to the underside of deck slab thus accelerating corrosion of reinforcement. Therefore, the expansion joints require maintenance and repair. Sometimes, the expansion joints are in very bad functional condition that it needs to be replaced. This requires extra effort in terms of money and time. Alternatively, bridges with integral abutments have the potential to be adopted as a competent solution for removing the leaking joint problem. It reduces the LCC by saving the construction cost as well as the maintenance cost (Feldmann *et al*, 2010).

The concept of integral abutment bridges is to connect the bridge deck slab to the abutments in such a way that the movement in the joints for expansion or contraction is ceased. Integral bridges are designed according to two basic concepts (Feldmann *et al*, 2010).

One of the concepts of integral bridges is constructing piles under the abutments with low flexural stiffness but sufficient vertical capacity. The reinforcement from deck slab and abutments are embedded in each other giving a monolithic connection. Long flexible piles are driven deep into the underground soil below the abutments. The piles which are embedded in the abutment make the overall bridge structure as a frame structure. Due to the long shape of the pile the frame structure behaves as flexible structure creating a hinge support between the deck slab and the abutments. In this way a low degree of restraint is achieved and the moments at the abutment corners are kept low (Feldmann *et al*, 2010).

The other common concept of integral bridges is constructing piles under the abutments with high flexural stiffness. The piles are stiff enough to support the higher moment at the abutment corner. As the substructure is strong so a very slender superstructure can be constructed (Feldmann *et al*, 2010).

4.6.1 New York State Department of Transportation's experience

The New York State Department of Transportation (NYSDOT) has constructed several integral abutment bridges since 1970s and they have shown excellent life performance (Collin *et al.,* 2006).

According to the NYSDOT concept of integral abutment bridges, the piles with low flexural stiffness are used. However, the deck slab and the approach slab are connected by a joint without the transition of horizontal reinforcement across deck slab and approach slab. The detail design of these integral abutment bridges allows rotation of the approach slab at the abutment to accommodate any occurred settlement. To accomplish this concept the transition reinforcing bars at the joint are placed at 45° into both the deck slab and approach slab. These transition reinforcing bars are joined with the stirrups at the connection between the prestressed beam reinforcement and abutment reinforcement. According to the guide lines of NYSDOT, a maximum of 190 meters long integral abutment bridge can be constructed (Collin *et al.,* 2006).

4.6.2 United Kingdom experience

In UK the portal frame configuration is used for the construction of integral bridges. In such a portal frame the end supports acts as retaining walls. The bridge deck beams and the supporting structure are constructed with the intention to achieve full moment continuity and accommodating the thermal expansion and contraction (Collin *et al.,* 2006).

The designers in UK use end screen walls supported on a small number of piles or an end screen wall sitting directly on the soil or end screen wall separated from the foundation (Collin *et al.,* 2006).

4.6.3 Swedish practices of integral abutment bridges

In Sweden, the concept of end screen walls is adopted for bridges with integral abutments. As shown in Figure End screen wall is connected with the bridge deck slab without joint and behaves as a cantilever structure. Piers are constructed to transfer the vertical forces to the ground. Sometimes bearings are used at the top of piers and sometimes not. In this way less vertical forces are transferred to the embankment soil thus reducing the risk of settlement at the approach slab (Kerokoski, 2006).

Some innovative integral abutment bridges have also been constructed in Sweden. In this concept, the piles of the integral abutment are driven below the lower edge of the back wall. The pinned connection is created between the back-wall and the piles. Then the steel tubes are placed over the piles and loosely packed sand is filled around the piles to minimize the pressure. The normal force and moment of the earth pressure against the back wall is accommodated by creating spring elements in the specified positions (Collin *et al.,* 2006).

In serviceability limit state, the yield strength of the steel components is used to prevent plastic deformation and decelerate the strains for delaying the collapse. The capacity in the ultimate limit state is limited by buckling and by moment/rotational capacity (Collin *et al.,* 2006).

4.6.4 German design of integral abutment bridges

In Germany, the bridge deck slab is constructed integrally with the abutment in such manner that a frame action is created. If the bearing capacity of the soil under the abutment is high then shallow foundation is constructed just beneath the abutment wall. For soil with poor bearing capacity, piles are driven deep into the soil under the abutment walls. In both type of foundation details the aim is to acquire slender slab structure to reduce the dead weight. The abutments are connected to the bridge deck slab in such a manner that a construction joint is created which is an essential feature of frame structures. This is achieved by the proper overlap of reinforcement between the bridge deck slab and abutment (Collin *et al.,* 2006).

5 Ultra High Performance Fiber Reinforced Concrete (UHPFRC)

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is the latest available form of advanced concrete, characterized by very low permeability, high ductility and good tensile strength in combination with high compressive strength of concrete. Principally, UHPFRC is a homogeneous, compact and ductile material. Homogeneity is obtained by removing the coarse aggregates used in Normal Strength Concrete (NSC). Compactness is obtained by using the optimum sized fine materials such as sand, silica and Superplasticizer. Ductility is obtained by using the high strength fibers. The comparison of the UHPFRC, Fiber Reinforced Concrete (FRC) and Normal Strength concrete (NSC) for uniaxial tensile and compressive stress states can be seen in Figure 5.1. It shows that the UHPFRC has a pronounce strain hardening behavior in tension, which makes it a unique concrete product (Habel, 2004). In this section this new material is presented and its potential as a future building material for Bridges is investigated.

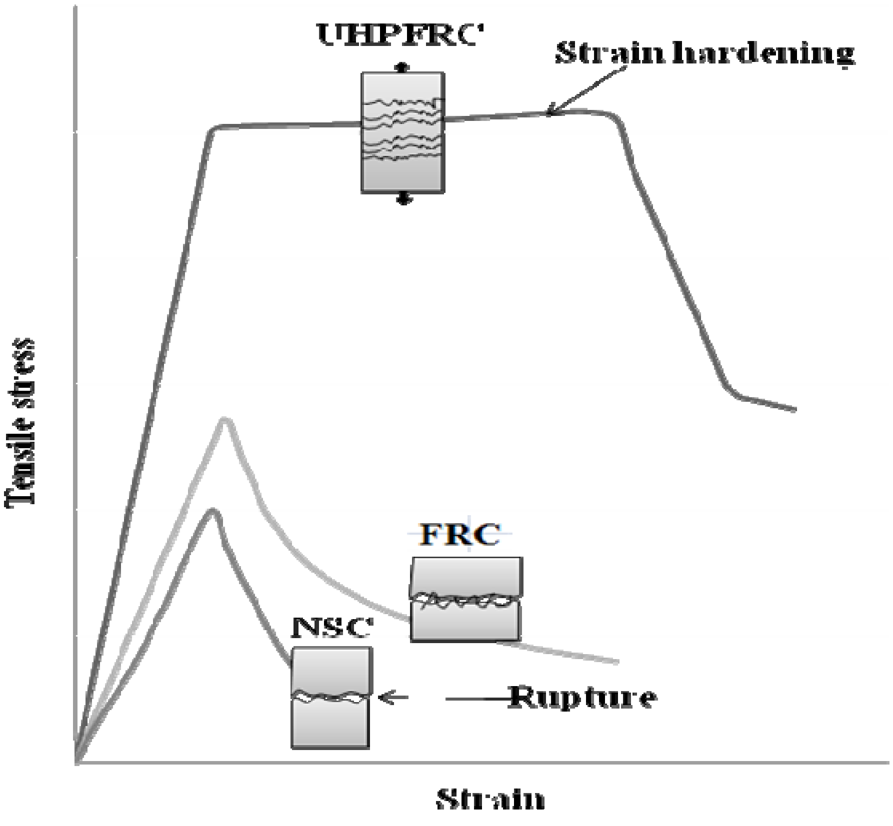


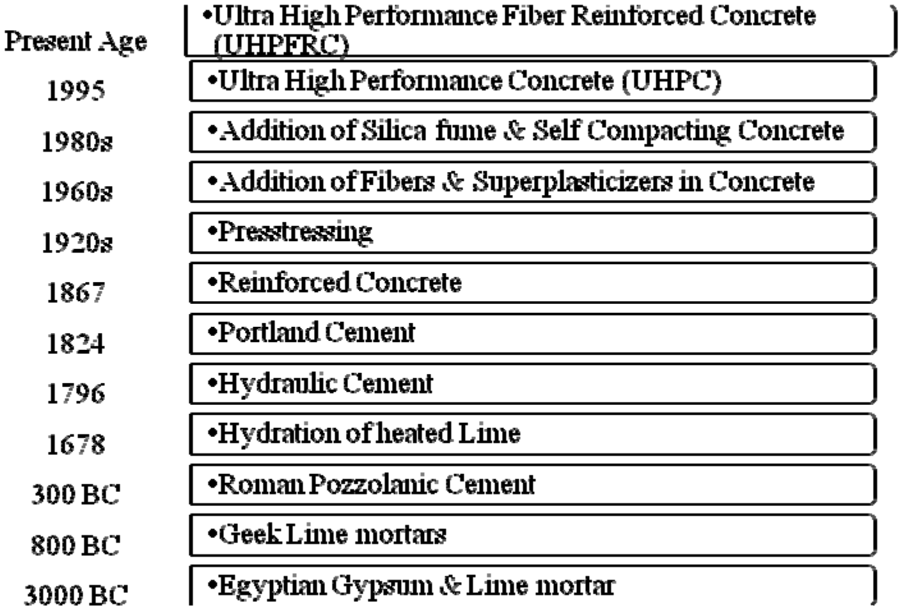
Figure 5.1 Typical behavior of UHPFRC in a uniaxial state of stress in comparison to other concrete mixtures. Adapted from Spasojević (2008)

5.1 Historical overview

Concrete has been one of the most widely used building materials because of its high compressive strength, resistance to water and good workability. Normal Strength Concrete (NSC) is a controlled mixture of Portland cement, water, fine aggregate, coarse aggregate and air. Portland cement is a material composed of Lime (CaO), Silica (SiO_2), Alumina (Al_2O_3) and Iron Oxide (Fe_2O_3). Fine aggregate is usually sand which has a chemical composition of Silica (SiO_2) found in the shape of fine granular material obtained by the process of erosion of rocks. Coarse aggregate is a term used for the coarse granular material used in concrete obtained from rocks but larger in the size from sand. When cement is mixed with water it hydrates and become stiff, binding the sand and gravel into a compact solid mass. The hydration reaction results in a liquid gel. Due to the hydration process this liquid gel gets hardened and gains strength which makes concrete a vital product for construction. NSC has a Young's modulus (E) of 14 to 42 GPa. The compressive and tensile strength of NSC ranges from 12MPa and 1.6 MPa for lower class (C12/16) to 90 MPa and 5.0 MPa for the highest class (C90/105) according to Euro code 2, (BS EN 1992-1-1).

NSC has a high compressive strength but weak tensile strength. Hence, NSC is mainly used for resisting compressive stresses while reinforcement is used to resist tensile forces in structural concrete. However, the low tensile strength and brittle response in tension results in cracking. The initiation of small cracks starts at very early stage. Later on, these small cracks develop into macro cracks. Together with the low ductility this makes NSC vulnerable to environmental actions and deterioration, which results in reduced life time of the NSC structure. Regular maintenance, repair and rehabilitation are performed to achieve a consistent life performance of NSC structures. This results in higher Life Cycle Costs (LCC) for NSC structures (Rossi & Chanvillard, 2000).

Over time, there has been a struggle to overcome these drawbacks in order to improve the performance of NSC. A view of the historical development of different concrete products can be seen in the Figure 5.2. Nowadays, different types of High Performance Concrete (HPC) products are available in the market.



Present Age	•Ultra High Performance Fiber Reinforced Concrete (UHPFRC)
1995	•Ultra High Performance Concrete (UHPC)
1980s	•Addition of Silica fume & Self Compacting Concrete
1960s	•Addition of Fibers & Superplasticizers in Concrete
1920s	•Presstressing
1867	•Reinforced Concrete
1824	•Portland Cement
1796	•Hydraulic Cement
1678	•Hydration of heated Lime
300 BC	•Roman Pozzolanic Cement
800 BC	•Geek Lime mortars
3000 BC	•Egyptian Gypsum & Lime mortar

Figure 5.2 Historical development of Concrete. Adapted from Spasojević (2008)

UHPFRC is currently the latest advanced High Performance Concrete product. In order to get a more homogenous product course aggregates are not used in UHPFRC mixtures. The density is increased by the use of silica fume along with sand and cement, contributing to the compactness. However, due to use of large volume of fine materials the mixture becomes brittle; therefore steel fibers are added to achieve a high range of ductility. The ductile behavior of this material enables it to deform and support flexural and tensile loads, even after initial cracking. Furthermore, the almost impermeable behavior of this material contributes to the long life performance by enhancing the durability (Habel, 2004).

5.2 Composition

Research began very early for increasing both compressive and tensile strengths of concrete. The structure, composition and strength of concrete have been studied at micro and macro level. As a result, Ultra High Performance Fiber Reinforced Concrete (UHPFRC) has been evolved which is a more flexible, workable, durable and strong concrete material. It has high compressive and tensile strengths along with high ductility (Rossi & Chanvillard, 2000).

UHPFRC consists of cement, sand, silica fume content, high super plasticizer, water and fibers. The water cement ratio is maintained at 0.15 to 0.20 (Habel, 2004).

The comparison of composition and properties of Normal concrete and UHPC can be seen in the Table 5.1.

Table 5.1. Comparison of composition and properties of NSC and UHPFRC. Adapted from Spasojević (2008)

Matrix composition		NSC	UHPFRC
	Component	Kg/m^3	Kg/m^3
	Portland cement	<400	700-1000
	Coarse aggregate	≈1000	0-200
	Fine aggregate	≈700	1000-2000
	Silica fume	-	200-300
	Superplasticizer	-	10-40
	water	>200	110-200
	Water-cement ratio	>0.35	<0.24
	Reinforcement/Fibers (kg/m^3)	No Fibers	>150
Properties	**Density (kg/m^3)**	2000-2800	>2500
	Compressive strength (MPa)	<60	>150
	Tensile strength (MPa)	<3	>8
	Modulus of elasticity (GPa)	≈30	50-70
	Fracture energy (J/m^2)	30-200	>10000

5.2.1 Cement

The cement content used is larger than 700 kg/m^3. The amount of cement is two times higher than in NSC. The quality of cement used should have low alkali content to avoid ettringite formation and reduce the heat of hydration (Habel, 2004).

The higher volume of cement reduces the heterogeneity and there are fewer pores in the concrete, resulting in lower internal restraint forces due to plastic shrinkage compared to NSC (Spasojević, 2008).

5.2.2 Sand

Quartz is recommended as fine aggregate which increases the compressive strength of UHPFRC. The optimum size used is less than 1 mm. however, an optimized grain size distribution should be obtained between cement, sand and silica fume to achieve good compactness and very low permeability. It enhances the stiffness and smoothen the overall texture of the hardened material. It also contributes to the high density of the product (Habel, 2004).

5.2.3 Silica fume

The content of silica fume used is 25% of the cement content. The use of silica fume is very useful to fill the voids and by forming a denser hydration product. It enhances the compactness and mechanical strength (Habel, 2004).

Silica fume acts as filler by filling the pores between the cement particles, making the UHPFRC an almost impermeable material compared to NSC (which has 20-25% pores). In addition, it reacts chemically with cement forming the dense cement gel compound resulting in well developed bond, which increases the mechanical properties. It also increases the viscosity of the UHPFRC which makes the mix a self compacting material (Spasojević, 2008).

5.2.4 Superplasticizer

Polycarboxylates and polycarboxylatethers are used as Superplasticizer for good workability. High efficiency is achieved as it has low water cement ratio compatibility (Habel, 2004).

5.2.5 Fibers

The use of fibers in UHPFRC increases the strength and ductility of concrete by delaying the process of localization of cracks and bridging the cracks. Thus, improving the post cracking behaviour of UHPFRC by introducing strain hardening (Rossi & Chanvillard, 2000).

Different types of fibers are used, characterized by their material, size and shape. Both steel and synthetic fibers are used to meet the requirement on strength and stiffness. On the market, the available steel fibers have a modulus of elasticity of 200 GPa and the strength is in the range of 1000 - 3000 MPa. Such high strength fibers are essential to transfer the tensile forces between small cracks safely. Different fibers are available with respect to shape and size. The prominent used fibers are short and straight fibers, and long fibers with hooked ends (Spasojević, 2008). However, the size and amount of fibers used depend on the need for ductility and workability. Usually, short fibers, long fibers or a mixture of both short and long fibers of metal or steel is used (Habel, 2004). The size and amount of metal fibers has a great influence on the mechanical behavior of the concrete structure and in particular the crack formation and crack propagation. A large amount of short fibers are useful in the crack initiation stage.

While in case of macro cracks the small amount of long fibers are useful (Rossi & Chanvillard, 2000).

5.3 Types of UHPFRC

There are different types of UHPFRC materials available on the market, differing mainly regarding their mixture composition. Mainly there are three types of UHPFRC mixtures which are Compact Reinforced Composites (CRC), Reactive Powder Concrete (RPC) and Multi-Scale Fiber Reinforced Concrete (MSFRC). Following the idea of these three types, different brands of UHPFRC are available on the market, developed by different companies. The modification has been done in these three types according to the composition of the mixture. The bending tensile strength of Compact Reinforced Composite (CRC) is much higher compared with other types of UHPFRC because of the use of conventional concrete. Its bending tensile strength has been obtained by using four points bending tensile test, while the bending tensile strengths of other brands is achieved by uni-axial tensile test (Rossi & Chanvillard, 2000).

Different types of UHPFRC materials and brands are listed and described in the Table 5.2 below.

Table 5.2 Mechanical prosperities of different type of UHPFRC. Adapted from CRC Tech (2011, Richard & Cheyrezy (1995), *Rossi & Chanvillard (2000),* ductal-lafarge (2011), *Rossi (2008), Spasojević (2008)*

Mechanical properties	**CRC**	**RPC**	**Ductal®**	**CEMTEC$_{\text{multiscale}}$®**	**BSI®**
Compressive strength (MPa)	140-400	200-800	150-200	180	190
Bending tensile strength (MPa)	30-200	30-50	25-40	25	9
Young's Modulus (GPa)	40-80	50-60	50-55	50	60
Density (kg/m$^{3)}$	2600-3000		2500	2500	2700

Compact Reinforced Composite (CRC)

One of the UHPFRC types is called Compact Reinforced Composite (CRC) and was developed by the company Aalborg Portland in Denmark. It consists of high percentage of conventional reinforcement and short sized strong metal fibers. CRC contains 5 to 10% of 6 mm long and 0.15 mm diameter metal fibers. The high percentage of conventional reinforcement increases the ductility of the material but is, on the other hand, more vulnerable to formation of cracks because of the stress concentration around the conventional reinforcement. In order to control the large number of cracks short fibers are used. However, it is pretty hard to install the large amount of conventional reinforcement as it is time consuming and requires extra skill and labour (Rossi & Chanvillard, 2000).

The four points bending tensile test shows a very high range of tensile strength for CRC. It is because of the use of closely spaced conventional reinforcement along with metal fibers which makes the CRC structure extremely ductile. The water/powder ratio is in the range of 0.15 to 0.20 which makes the wet mixture a self compacting material. The durability of CRC is very high compared to NSC. Practically it has very less amount of pores which makes it almost impermeable material. Non-existence of pores means, no water inside the CRC structure. Therefore no freeze and thaw problem is found in CRC structures. The mechanical properties of CRC are briefed as shown in Table 5.2 (CRC Tech, 2011).

Reactive Powder Concrete (RPC)

Another type of UHPFRC is called Reactive Powder Concrete (RPC), developed by a company called Bouygues in France. It consists of fibers twice the length and half the percentage of CRC. RPC contains a maximum of 2.5% of 13 mm long and 0.16 mm diameter metal fibers with water/powder ratio of 0.15 to 0.19. Due to less amount of fibers used in RPC, the uniaxial tensile strength is confound to 8 MPa only. With such a low amount of fibers the post cracking behavior was variable. However, if the orientation of the fibers is kept orthotropic, perpendicular to the flexural cracks, than a homogenous and ductile product can be obtained (Rossi & Chanvillard, 2000).

Two types of RPC products are used depending on their compressive strength. One is RPC 200 which has a compressive strength of 200 MPa and other is RPC 800 which has a maximum compressive strength of 800MPa. A compressive strength of 800 MPa is achieved by using steel aggregates instead of quartz sand and applying a pre-heated pressure of 50 MPa. The mechanical properties of RPC are briefed as shown in Table 5.2 (Richard & Cheyrezy, 1995).

Multi-Scale Fiber Reinforced Concrete (MSFRC)

Further development showed another type of UHPFRC called Multi-Scale Fiber Reinforced Concrete (MSFRC) developed by the Laboratoire Central Des Ponts et Chaussées (LCPC) in France. It consists of both short and long sized fibers. The amount of short fibers used in this mixture is 5 % which are straight in shape, having length of 5 mm and 0.25 mm in diameter. 2% of hooked end long fibers with 25 mm length and 0.30 in diameter are used. Because of the mixed use of short and long fibers it gives good results for workability, ductility and tensile strength (Rossi & Chanvillard, 2000).

Ductal$^{®}$

Ductal$^{®}$ is a high strength ductile UHPFRC product developed by Lafarge, Bouygues and Rhodia in France. This is obtained by using the idea of RPC. It consists of 2% of 12 mm long and 0.2 mm diameter fibers with water/cement ratio of 0.20 to 0.26. There are two types of fibers used in Ductal® that is High Carbon Metallic or Poly-Vinyl Alcohol (PVA) fibers. With the use of this technology thinner, lighter and more graceful structures can be made having good ductility and less permeability. It has a very low porosity compared to NSC which makes the Ductal$^{®}$ an almost impermeable material. The mechanical properties can be seen in the table 5.2 (ductal-lafarge, 2011). The amount of fibers used in this product is very less compared to other types of UHPFRC. With the use of hooked and twisted shaped high strength fibers the same strain hardening behavior can be obtained as the other UHPFRC product exhibit with 5 to 10 % fibers (Kim *et al.* 2008).

CEMTEC$_{\text{multiscale}}^{®}$

CEMTEC$_{\text{multiscale}}^{®}$ is a type of UHPFRC introduced in France. This is obtained by using the idea of MSFRC. It contains 11% fiber with the ranging from shorter than 1 mm up to 20 mm long (Rossi, 2008). The mechanical properties can be seen in the Table 5.2.

Béton Special Industriel (BSI$^{®}$)

BSI$^{®}$ (Béton Special Industriel) is a type of UHPFRC developed by the company EIFFAGE in collaboration with cement manufacturer SIKA in France. It contains 2.5 % fibers with water/cement ratio of 0.22. With correct casting procedure, the required strain-hardening behavior of typical UHPFRC can be obtained in spite of use of such low quantity of fibers (Spasojević, 2008). The mechanical properties can be seen in the Table 5.2.

5.4 Properties of fresh UHPFRC

5.4.1 Workability

UHPFRC has the advantageous property of being self-compacting. To achieve this behavior, the mixture should be design in such a way that it gets good workability. However, the composition of the UHPFRC mixture should be selected in such a way that the basic characteristics of homogeneity, compactness and ductility should not be compromised.

The required workability can be obtained in a controlled environment for pre-cast UHPFRC materials. However, to use UHPFRC as cast-in-situ construction material for bridges, the workability issue should be addressed with a much realistic approach.

As there is low amount of water used in UHPFRC, therefore, the amount of cement, silica, Superplasticizer and fibers should be selected in such a proportion to achieve the required workability along with strength and ductility (Habel, 2004).

Addition of super plasticizers enhances the workability of the UHPFRC mixture. Superplasticizer is added in UHPFRC mixture before and also after addition of water. A step wise addition of Superplasticizer enhances the fluidity of UHPFRC mixture. It also reduces the viscosity of the UHPFRC mixture lowering the air content (Tue at al. 2008).

5.4.2 Hydration and heat generation

Hydration is the exothermic process in which reaction of Portland cement with water and reaction of additives such as silica fume takes place. The degree of hydration is defined as the ratio between the amount of cement or binders hydrated to the initial amount of cement or binder.

UHPFRC consist of very low water cement ratio which delays the full hydration of cement contents Habel K. (2004). As an example UHPFRC with water cement ratio of 0.18 and with 26% amount of silica fume showed a 31% final degree of hydration.

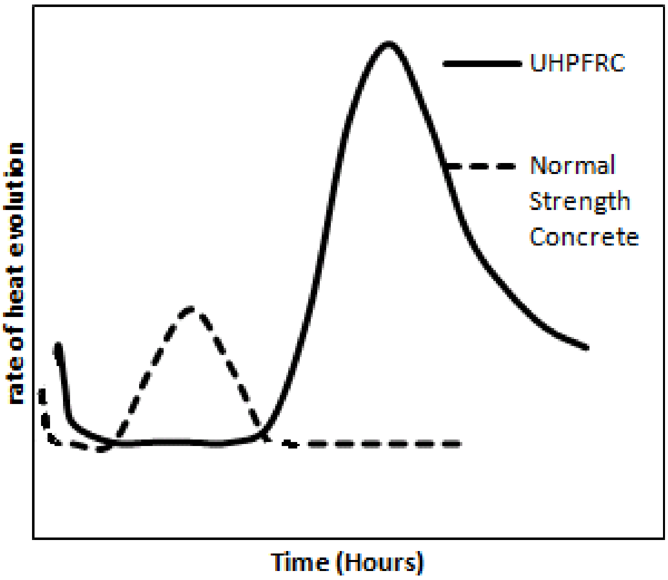


Figure 5.3 Evolution of the degree of hydration of UHPFRC and NSC. Adapted from Habel (2004).

In the fig above, there is a long dormant period typically for 24 hours or long due to addition of super plasticizers which delay hardening of concrete. Then strong hydration reaction starts and heat is released. There is increase in degree of hydration between 30 and 57 hours for UHPFRC. While for normal strength concrete there is small dormant period of 2 to 4 hours. After this stage cement starts to hydrate and releases heat. Final stage of hydration finishes either with complete hydration or unhydrated cement left when no water is available for hydration. In the previous researches a model was proposed for hydration of normal strength concrete that only complete hydration of cement content can occur if water-cement ratio is of 0.42 Denarié *et al*. (2009). Later Habel (2004) used this model for predicting the degree of hydration of UHPFRC. Furthermore, it was also shown that the degree of hydration of UHPFRC is very low and cement content of UHPFRC does not hydrate completely.

In 2004, Habel conducted semi-adiabatic tests on UHPFRC to find the temperature generated during hydration. Figure 5.4 shows that temperature of UHPFRC is constant until 24 hours and rapidly increases until 36 hours after mixing. However after that temperature becomes slow down and finally temperature reaches between 100°C to 120°C. The initial dormant period is due to use of super plasticizer. While dormant period is shorter in normal strength concrete and evolution of heat is also less than UHPFRC. Hydration of UHPFRC releases almost double the amount of heat released by normal strength concrete (Habel, 2004).

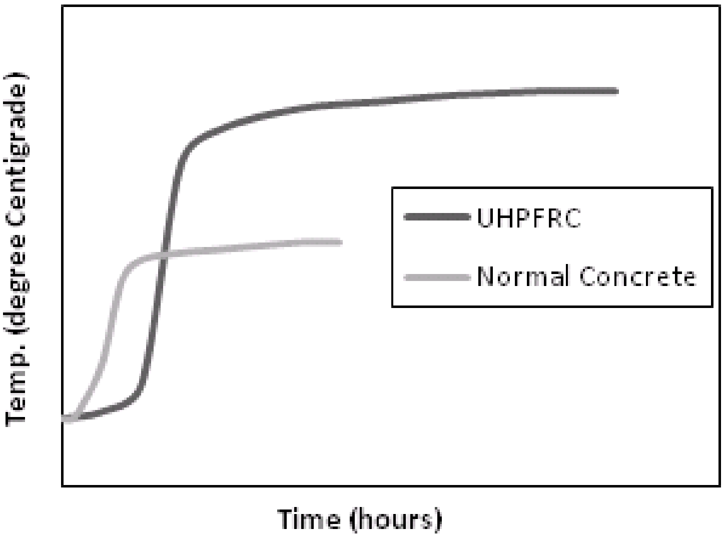


Figure 5.4 Temperature rise in UHPFRC and Normal concrete during hydration. Adapted from Habel (2004).

5.4.3 Self dessication

One of the detrimental effects of using low water/cement ratio in UHPFRC is self dessication. In this process, concrete becomes dry from inside due to the consumption of moisture during the hydration reactions. The result is that the hydration of the concrete terminates if addition moisture is not provided creating empty capillary porosities within cement paste micro structures, which can affect the durability properties of UHPFRC. However, detrimental effects can be controlled by special attention to curing (Carino & Meeks, 1999).

5.5 Material properties for the hardened UHPFRC

5.5.1 Permeability

Bridge deck slabs and their connecting elements are among the most vulnerable to chloride ingression. Deterioration due to corrosion of reinforcement is the most common problem with these structures. Moreover, the transport of chloride and oxygen inside the cracks also facilitates the process of corrosion. UHPFRC presents a very low permeability which makes it an attractive construction material to be used in structures exposed to water and aggressive solutions. Therefore UHPFRC may be used as construction material to control the corrosion deterioration in such susceptible areas. UHPFRC not only provides protection but also enhances the load carrying capacity of the structure (Charron *et al.*, 2006).

To study the permeability of UHPFRC under high stresses, one of the researches has been conducted at the Swiss Federal Institute of Technology (EPFL). Uni-axial tensile and permeability tests were conducted on the UHPFRC called $\text{CEMTEC}_{\text{multiscale}}^{®}$. The specimens were cured for 28 days and Uni-axial tensile tests were carried out to get desire deformation of 0.13, 0.25, 0.5, 0.75 and 1%.

Table 5.3 Constituents of UHPFRC specimen. Adapted from Charron et al. (2006).

Component	**Content (kg/m^3)**
Cement-CEMI 52.5	1051
Silica fume	273
Sand (d_{max}=0.5 mm)	733
Steel fibers (l/d=50)	468
Water	165
Super-plasticizer	35
W/binder ratio	0.140

It was also observed that cracking did not influence equivalent water permeability of core specimen significantly until deflection of ϵ_t = 0.13 mm for 100 mm specimen and for NSC it was 0.05 mm. Furthermore, the permeability of uncracked UHPFRC was found 1×10^{-10}cm/s and for NSC it was found 5×10^{-9}cm/s. This difference between is due to multiple micro-cracking in UHPFRC instead of few micro-cracks develop in NSC. While micro-cracks are less permeable than discrete cracks in normal strength concrete (Charron *et al.*, 2006).

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5.5.2 Mechanical response in tension

Strain hardening is one of the most distinguishing characteristics of the UHPFRC. The Tensile behavior of UHPFRC is shown in Figure. 5.5. Elastic deformation is obtained up to point A. At this stage, multiple micro cracks develop in the concrete. Strain hardening response is till point B and this effect is due to the pull out behavior of the fibers. The deformation in UHPFRC is still uniformly distributed and can be expressed by the strain ε. After point B, localization of cracks occurs and a softening behavior starts. The deformation behavior can then be expressed by stress-crack opening curve as shown in Figure. 5.6 (Habel, 2004).

Many researchers have done experiments to examine the deformation behavior of UHPFRC. Charron *et al.* (2006) performed uniaxial tests on specimen (prisms of $50\times200\times500\text{mm}^3$), to study the tensile behavior of UHPFRC. The maximum tensile strength was found 10.8 MPa for displacement of 0.25 mm as compared to 0.015 mm displacement of normal strength concrete. After that localization of cracks occurred and at a displacement almost equals to the fiber length there was no transfer of stress by material (Charron *et al.*, 2006). The softening behavior is described by a stress-crack opening relationship. The stress-crack opening curve is characterized as Fracture Energy, which is much larger for UHPFRC than for normal strength concrete. The mechanical properties of UHPFRC are greatly affected by the distribution of fibers. Consequently, the shape and flow of material in mould while casting the concrete must be taken into account (Habel, 2004). See also section 5.5.5.

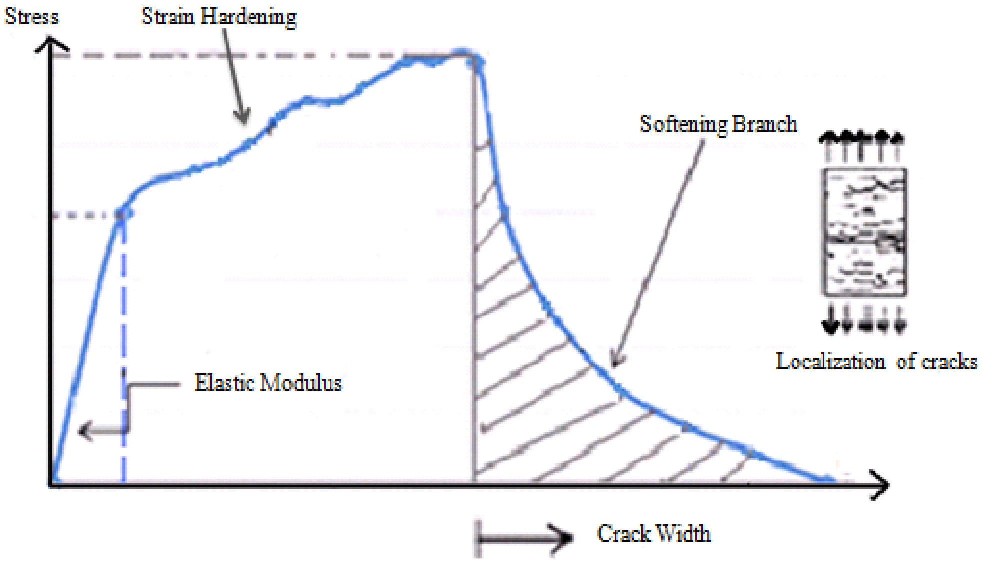
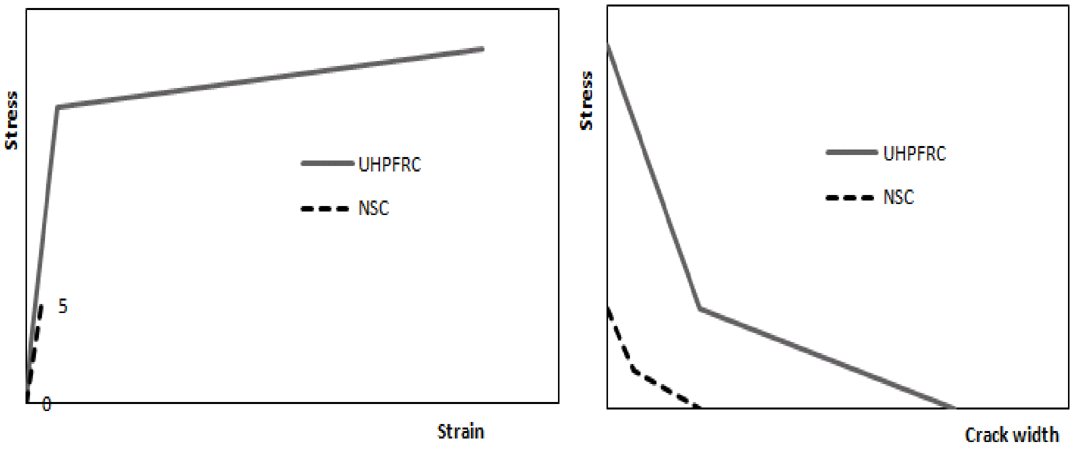


Figure 5.5 Typical stress-strain response of UHPFRC. Adapted from Habel (2004)



(a) **(b)**

Figure 5.6 (a) Shear-Strain response before crack localization and (b) Stress-crack opening response after localization

The load displacement relationship from a tensile test cannot be directly translated into stress–strain relationship because of the localization of cracks after maximum load as shown in figure 5.7. Instead materials properties should be divided into an elastic stress-strain relation and a stress crack opening relation. In normal strength concrete, after crack initiation the deformation increases while the material becomes unloaded (Plos, 2000). In case of UHPFRC, a large number of micro cracks develop in the concrete after the crack initiation. This stage is called strain hardening and is a major principal difference in response, distinguishing its tensile behavior from normal strength concrete.

5.5.3 Mechanical response in compression

UHPFRC has a compressive strength of more than 150 MPa and shows a ductile post-peak behavior due to stress-transfer mechanism of the micro cracks. The elasticity modulus, E is in range of 50-70 GPa. Ultra High Performance concrete (UHPC) shows brittle behavior under compression, but addition of fibers impairs the effect of the brittle behavior and also increases the compressive strength as shown in Figure 5.7 (Spasojević, 2008).

The post peak behavior is affected by the aspect ratio of fibers (l_f/d_f), fibers orientation, shape of fibers and, bond between fibers and matrix (Spasojević, 2008)(Denarié, 2009).

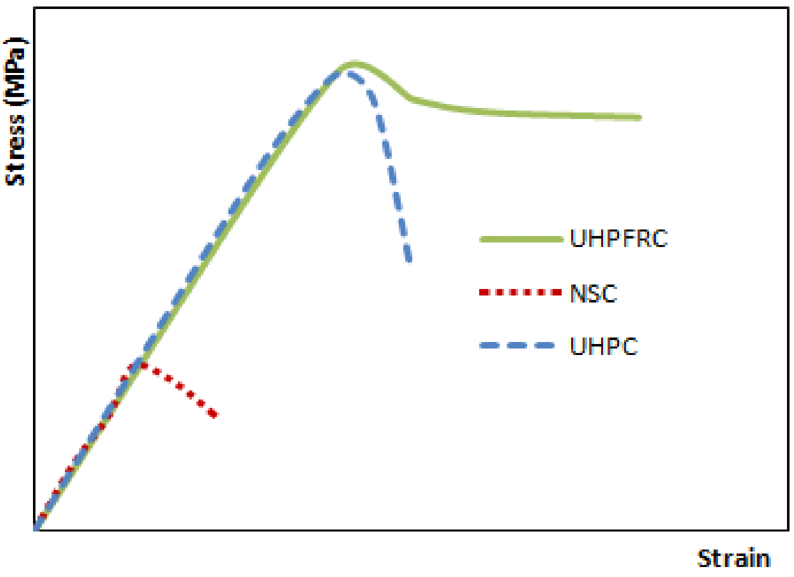


Figure 5.7 Stress-strain relationship of different UHPFRC's in Compression. Adapted from Spasojević (2008)

The figure above shows the compressive behavior of the UHPFRC, Ultra high performance concrete without fibers and normal strength concrete. There is linear stress-strain relationship before peak load. Post-peak part is non linear and shows the softening behavior of the UHPFRC. While ultra high performance concrete shows brittle behavior after peak load.

5.5.4 Effect of fibers on mechanical properties

Different researches have shown that the orientation and distribution of fibers significantly affect the mechanical properties of UHPFRC.

To study this, Lataste *et al.* (2009), conducted experiments on UHPFRC with fiber content 2%. It was found that cube compression test showed that the fiber alignment has no significant effect on the compressive strength. However bending tests on round panels indicated that the distribution and orientation of fibers greatly affect the flexure strength of the UHPFRC. From the observation it was clear that "fibers tended to align perpendicular to the direction of flow of fresh concrete." As a result the panel casted from the centre showed higher flexural strength than the panels casted from the edge. The researches indicated the importance of the behavior of UHPFRC under loading and the correct casting techniques (Lataste *et al.*, 2009).

5.5.5 Thermal expansion

Most materials expand when subjected to increased temperature. This needs to be accounted for structural design as the expansion of materials induces thermal strains which further leads to stresses and possibly cracking of concrete. For the temperature range normally designed for, the free thermal expansion is linear, and a constant coefficient of thermal expansion can be used.

UHPFRC is a composite material; its thermal coefficient is co-related with its constituents. Some factors affecting the thermal coefficient are water-cement ratio, curing regimes, fineness of cement and age of concrete at the time of testing. Graybeal B A. (2006), conducted tests to investigate the thermal expansion of UHPFRC at different ages in four curing regimes. The thermal expansion of UHPFRC was found to be around 15 x 10^{-6} mm/mm/°Celsius, which is higher than the normal thermal expansion of value of normal strength concrete i.e. 10 x 10^{-6} mm/mm/°Celsius (Graybeal, 2006).

5.5.6 Shrinkage

The low water-cement ratio leads to self desiccation of UHPFRC. In the process of self desiccation, the internal relative humidity of the concrete decreases during hydration which reduces the pore size and provokes capillary tension in the pores. This leads to rapid development of autogenous shrinkage of UHPFRC at early age. However there is only insignificant moisture exchange with the environment i.e. no drying shrinkage. Major part of shrinkage occurs immediately after setting (Kamen, 2006) (Domone & IIlston, 2010).

Kamen (2006), performed tests on sealed prism 7×7×28cm^3 in room temperature of 20±2^{o}C and relative humidity of 65% to check the autogenous shrinkage. The value of 542 μm was obtained after 365 days. The 39 % of this shrinkage was obtained after 7 days and 85 % was obtained after 90 days. The rate of autogenous shrinkage became constant after 285 days as shown in Figure 5.8.

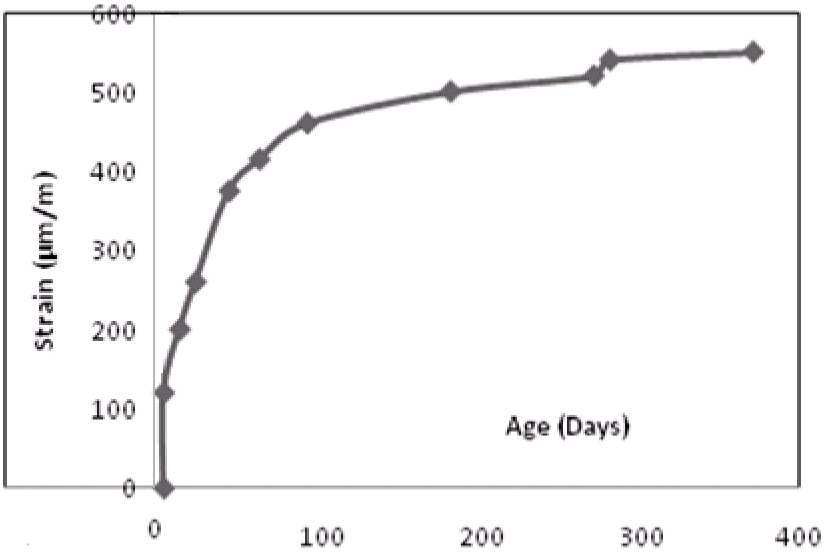


Figure 5.8 Long term autogenous shrinkage at 20^{o}C. Adapted from Kamen (2006)

Kamen (2006) also performed the same type tests but with changing curing temperatures to check the influence of curing conditions on shrinkage. The results indicate the increase of autogenous shrinkage with increasing curing temperature as shown in Figure 5.9.

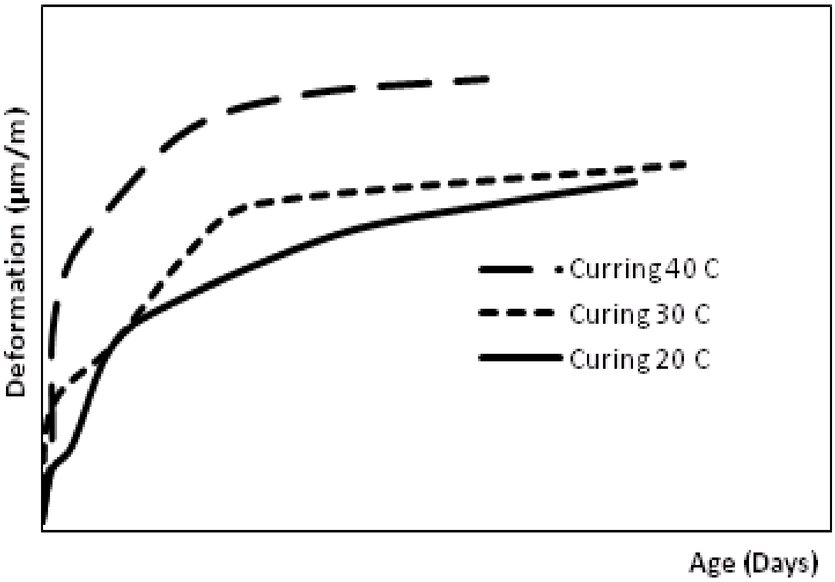


Figure 5.9 Autogenous Shrinkage for various curing conditions. Adapted from Kamen (2006)

The presence of fibers in the UHPFRC reduced the shrinkage deformation to 35% as compared to a matrix of ultra high performance concrete as shown in Figure 5.10.

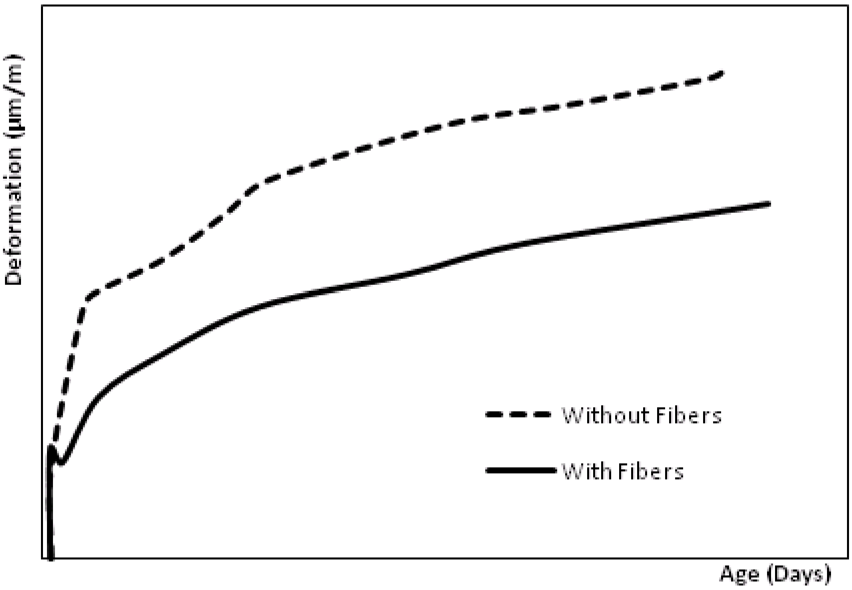


Figure 5.10 The influence of fibers on shrinkage in UHPFRC with and without fibers. Adapted from Kamen (2006)

5.5.7 Creep

Creep is defined as gradual increase in deformation under sustained loading. Young UHPFRC shows large creep deformation under compressive loading, particularly the in the first days. Creep behavior is closely related to Shrinkage and creep is significantly reduced by thermal curing of the specimens. Different research studies have been made to study the compressive and tensile creep behavior of UHPFRC.

Compressive creep tests on CEMTEC$_{\text{multiscale}}^{®}$ were done in Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland. Stress levels of 25, 43 and 55% of the compressive strength at the time of loading were applied on the test specimens. The creep behavior was investigated at the age of 3 and 7 days for sealed as well as free specimens. The 3 days old specimen was found more vulnerable to creep than the 7 days old specimen. The creep magnitude increases more for high stress levels (Kamen *et al*., 2007).

Tensile creep tests are complicated to perform and this inadequacy is because of the complex variation in physical and chemical properties of UHPFRC at early age. UHPFRC shows viscoelastic behavior under tension and still it is not completely known. An accurate structural analysis considering cracking damage is not possible without correctly modeling the viscoelastic behavior of UHPFRC at early age. This viscoelastic behavior minimizes the risk of cracking by reducing the effect of early age restraint stresses (Kamen *et al*., 2008).

Kamen *et al*. (2008) performed some tests on CEMTEC$_{\text{multiscale}}^{®}$ to observe the tensile creep behavior. They observed that creep rate is higher in early age after loading of specimen and later on decreases due to increase in stiffness and mechanical strength i.e. creep is inversely related with loading age as shown in Figure 5.11.

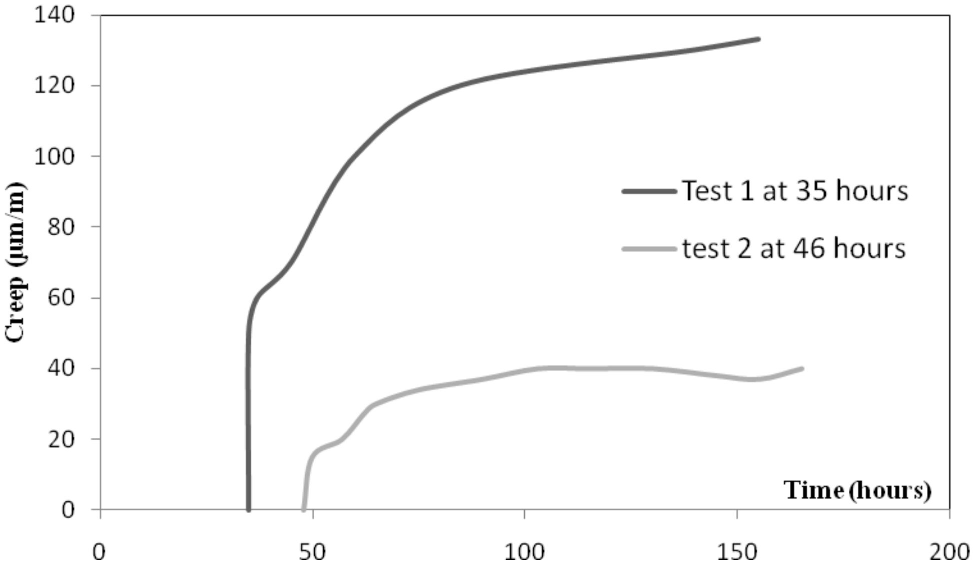


Figure 5.11 Creep results at different age of loading. Adapted from Kamen et al., (2008)

In the above figure creep behavior of two CEMTEC$_{\mathrm{multiscale}}$$^{®}$ specimens is shown. Creep rate is higher for 35 hours than 46 hours. From the tests results on CEMTEC$_{\mathrm{multiscale}}$$^{®}$, it was observed that that shrinkage almost stops after 90 days and viscoelastic behavior stabilizes afterwards. It is due to hydration reaction is shorter for UHPFRC due to self desiccation (Habel K., 2004).

5.5.8 Fatigue behavior

Fatigue is defined as the process of internal structural changes in a material under cyclic loading. It can be a possible failure mechanism for a structure subjected to repeated loading. Such as bridge deck slab which is subjected to the repeated load of traffic and the understanding of fatigue bending behavior is important.

NSC is more prone to fatigue failure due to its heterogeneous structure. It has pores, air voids, and trapped water content in the pores, freeze and thaw cycles and low resistance to tensile loading. The fatigue mechanism can be divided into three steps for NSC. First is the crack initiation stage, second is the crack propagation stage in which the formation of microcracks occurs and third is the failure stage in which the formation of macrocracks occurs. Furthermore, NSC exhibits no fatigue limit under the threshold limit of 2×10^6 cycles. Hence there is no known stress level below which the fatigue life of plain concrete will be infinite (Lee and Barr, 2004).

However, UHPFRC is much stronger material than NSC, in terms of, mechanical behavior and durability properties. Therefore, it is expected that UHPFRC will show better performance to fatigue loading than NSC when used as construction material for bridge deck slabs. In the second stage crack propagation causes the localization of microcracks. Hence, efforts can be done to retard crack growth in this stage. One of the possibilities is adding the fibers which will bridge these small cracks, inhibit the crack growth and increase the load carrying capacity of UHPFRC. It has been found that UHPFRC shows large number of small cracks under static loading, which is a bright characteristic of UHPFRC due to the addition of fibers, as; it is the aim of the designer to avoid formation of the large cracks during Serviceability Limit State (SLS). It seems from observations that UHPFRC shows better performance in the fatigue life under flexural fatigue loading than compressive fatigue life under compressive fatigue loading. It may be possible due to the bridging of cracks under tensile loading (Lee and Barr, 2004).

However, it has been found that UHPFRC undergo larger strains before failure than NSC. UHPFRC shows higher level of damage under static and fatigue testing. It has been also suggested that fibers enhances the fatigue behavior of UHPFRC under low cyclic loading only that is up to 10^3 cycles, approximately. Unlike NSC which has no fatigue limit, UHPFRC reaches a fatigue limit of 2×10^6 cycles. However, it is not confirmed yet that what the fatigue limit of UHPFRC is (Lee and Barr, 2004).

UHPFRC shows different behavior in fatigue loading compared to NSC. The response of UHPFRC is studied under uni-axial loading as it can be seen in the Figure 5.12. Figure 5.14 shows the development of strain versus number of cycles to failure under uni-axial. The response is divided into 3 phases based on the strain development. In phase I, the strain develops non-linearly up to 3% to 5% of the number of cycles to failure. In phase II, which is from 5% to 95% the strain increases linearly. And in the last phase the structure fails verified by rupture behavior. However, In NSC the linearity starts at 20% and rupture at 80%. Due to fibers in UHPFRC the damage process is slow and less brittle than NSC (Gunberg *et al.*, 2008).

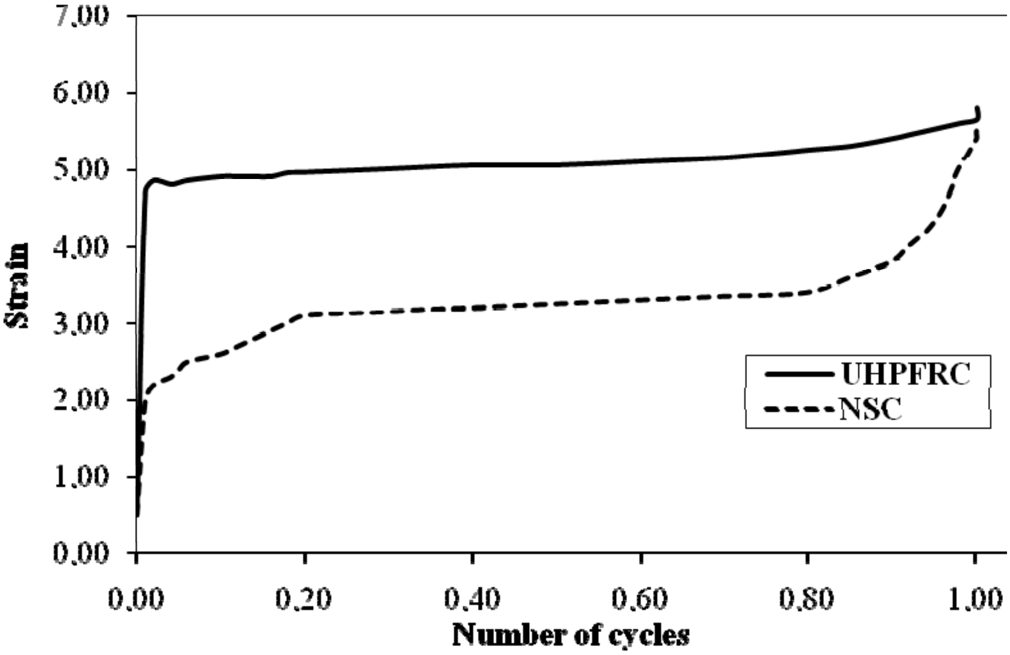


Figure 5.12 Development of strain vs number of cycles to failure for UHPFRC and NSC under fatigue loading. Adapted from Grunberg et al. (2008)

5.6 Durability properties

Durable concrete is defined as being able to resist weathering, chemical attacks, abrasion and other processes of deterioration. UHPFRC has much denser structure than ordinary concrete therefore it shows high durability due to significant reduction in pore size and volume. Pore volume ratio of capillary pores of UHPFRC is 4.3 - 4.5%, where for high strength concrete is 9% (Toutlemonde & Resplendino, 2011). Various researches have been done to determine the durability of UHPFRC in aggressive environments. In 2007, Graybeal and Tanesi made a research on the material property characterization of UHPFRC with 2 % fiber contents. They conducted durability tests on UHPFRC in four different curing conditions.

These curing regimes were steam curing in which specimens were steam cured in 90^{o} C for four days continuously, 2nd was normal curing method in which no extra heat treatment was applied, 3rd was tempered steam n which specimens were treated in 60^{o} C and last was delayed steam in which specimens were steam cured after 15 days. For in-situ bridge construction usually concrete is cured by ordinary curing methods.

5.6.1 Chloride penetration

Chloride ingress by diffusion or capillary suction causes corrosion of reinforcement in reinforced concrete. Permeability of the concrete plays an important role to stop the migration of chloride ions.

Graybeal and Tanesi (2007) have performed tests on UHPFRC having low w/b ratio and densely packed matrix, to find its ability to resist chloride ion penetration. Specimens were tested in sodium chloride and sodium hydroxide solutions. Electric potential was applied across a specimen load cell and the amount of current passing through the specimen was measured. It was found that UHPFRC has almost negligible chloride ion penetration when treated thermally and showed very low penetration when non-thermally treated. Normal strength concrete with 0.4 to 0.6 water-cement ratio showed high penetration of chloride ions as compared to UHPFRC as shown in table 5.5.

5.6.2 Freeze –Thaw resistance

Continuous freezing and thawing of saturated concrete leads to disintegration of concrete. Since water expands 9% when it freezes it will create hydraulic pressure inside the pore structure causing the expansion of concrete. This can eventually leads to cracking of concrete. The effect of Freeze-thaw cycles can be prevented by air entrainment or by using concrete with low w/c ratio.

Concrete requires extended durability in Swedish environmental conditions. UHPFRC contains very fine particles of binders and silica fume, which makes it almost impermeable as compared to normal strength concrete. Furthermore UHPFRC has a high tensile strength. Consequently it can be expected to have good resistance with respect to freeze-thaw cycles. A test series according to ASTM was performed on UHPFRC which was subjected to freeze-thaw cycles (Graybeal and Tanesi, 2007). In total 690 freeze-thaw cycles were applied on the specimens during 9 months. Over all the results confirmed the durability of UHPFRC under freeze-thaw conditions. Other researchers have shown 100% durability of UHPFRC when subjected to 300 freeze-thaw cycles (Habel *et al.*, 2008).

5.6.3 Alkali Silica Reaction

The reaction of alkalies in the cement with silica causes expansion of concrete, which later on may leads to cracking. Alkalies can also be contributed from admixtures and de-icing salts. In the presence of moisture, internal reaction takes place, causing disintegration of the concrete matrix.

Graybeal (2006) performed tests on specimens of UHPFRC according to ASTM to detect the possible effects of alkali silica reaction. In these tests, the specimens were subjected to different curing conditions. Then the specimens were placed in a sodium hydroxide solution in 80^{o}C. The expansion of the specimens was measured less than 0.1% after 14 days and less than the threshold value of 0.2% according to after 28 days. Alkali silica reaction needs water for completion in any concrete. However, due to the low permeability alkali silica reaction will stop when no water is available and it is harmless to UHPFRC. Furthermore, the curing conditions affect the ASR as shown in the results in Table 5.4. For more details see Graybeal and Tanesi, 2007.

Table 5.4 ASTM Alkali-Silica expansion results and chloride ion permeability for different curing regimes. Adapted from Graybeal (2006), Graybeal and Tanesi (2007)

Curing Regime	**14 days Expansion (%)**	**28 days Expansion (%)**	**Coulomb's Passed (Average)**	**Chloride Ion Permeability**
	Average	**Average**		
Steam	0.013	0.009	18	Negligible
Air (Standard)	0.011	0.012	360	Very Low
Normal Strength Concrete (water-cement 0.4-0.6)			2000-4000	High
Tempered Steam	0.005	0.004	39	Negligible
Delayed Steam	0.001	0.002	18	Negligible

5.6.4 Abrasion resistance

Abrasion is a form of deterioration caused mostly by studded tires and blades of snow clearing vehicles. To know the abrasion resistance of UHPFRC tests were conducted by Graybeal (2006), according to standards of ASTM. In this test a cutter with dressing wheels mounting on a rod is rotated on a specimen and the amount of concrete abraded is measured, which gives the resistance of the specimen to abrasion. Tests were conducted on three different concrete surfaces. It was found that thermally treated specimens lost between 0.1 to 0.3 grams of from total mass during abrasion. While thermally untreated specimens lost 1 –3 grams of mass. Furthermore, the finishing of the surface also modifies the abrasion resistance as shown in Figure 5.13. It was also observed that UHPFRC shows more abrasion resistance prior to the rupture of smooth cast surface while high performance fiber concrete shows constant abrasion resistance throughout during the test (Graybeal, 2006).

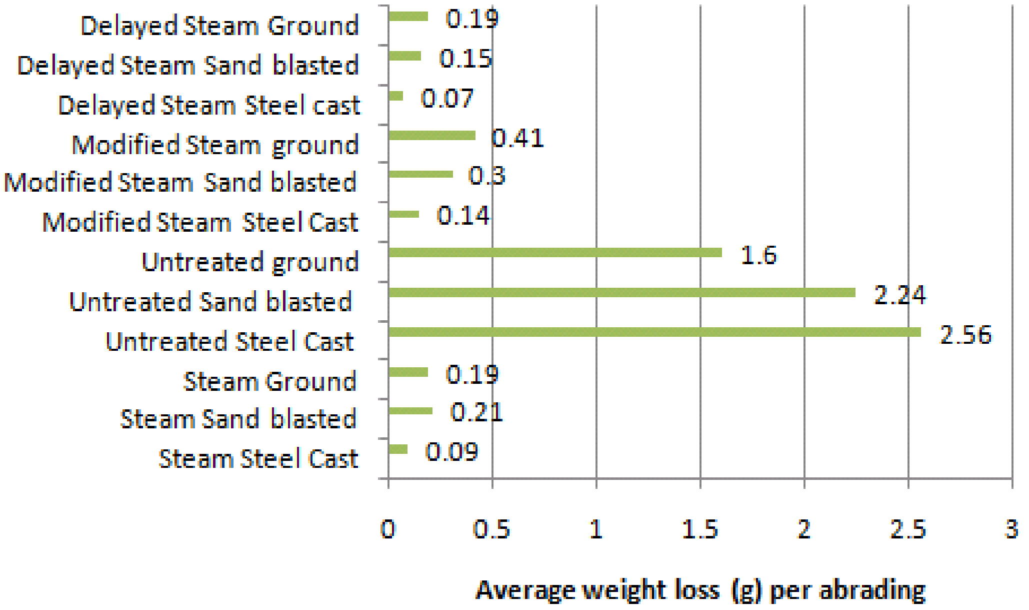


Figure 5.13 The chart shows the average weight loss (grams) per abrading under different curing conditions. Adapted from Graybeal (2006).

The figure above shows the weight loss of three concrete surfaces (finished under steel cast surface, sand blasted surface, and ground surface) in different curing regimes. The concrete finished under steel cast surface and cured with delayed steam shows the least value of abrasion as compared to other concrete specimens.

6 Application of UHPFRC to Bridge Decks

Bridge decks all over the world are facing increasing deterioration problems due to aggressive environment and de-icing salt. This leads to costly repair interventions that disturbs traffic and results in high life cycle cost for the bridges. Over the last few decades, considerable efforts have been made to improve the resistance of bridge decks against deterioration. UHPFRC is characterized by excellent mechanical properties and very low permeability which makes it a very suitable material to be used in aggressive environments. UHPFRC can be used as a construction material for new structures as well as for rehabilitation of existing structures. Composite UHPFRC structures provide long term durability, thus reducing the maintenance cost.

The superstructure as well as the substructure of shorter span bridges is usually constructed of concrete. This results in good aesthetical appearance keeping the construction cost low. For longer spans, it is common with composite bridges, combining steel girders with a concrete bridge deck and a concrete substructure. Concrete bridge deck with longer span is an important challenge because of the heavy weight of the concrete deck. UHPFRC exhibits excellent performance with respect to ductility combined with high compressive and bending strength. Therefore, UHPFRC can be used as a construction material for such bridge deck slabs adopting a slender section. Furthermore, low permeability in combination with durability makes it suitable to use as a protective overlay to the bridge deck slab. Also very good bonding properties of UHPFRC to reinforcing bars make it suitable for joining concrete elements that should act as one unit.

6.1 Rehabilitation with UHPFRC

The successful rehabilitation of existing structures is a big challenge to civil engineers because, when a new concrete layer is applied to an old concrete structure, a composite structure is formed. Consequently, internal tensile stresses will arise in the new layer due to restrained shrinkage. However both deformability and strain hardening behaviour reduce the intensity of these stresses and increase the service life of the structure (Habel, 2004).

One of the main purposes of rehabilitation is that a minimum of maintenance should be required during the remaining service life of the structure. Since the initial cost of UHPFRC is high, it has been proposed to use UHPFRC where the structure is more prone to attack by aggressive salts and chlorides, and where it has to resist the maximum mechanical loads. Habel *et al.* (2006) investigated the structural response of elements combining UHPFRC and reinforced concrete. They proposed three different configurations of combinations with recommendations for material properties denoted by P, PR and R for rehabilitation and modification of reinforced concrete members as shown in Figure 6.1.

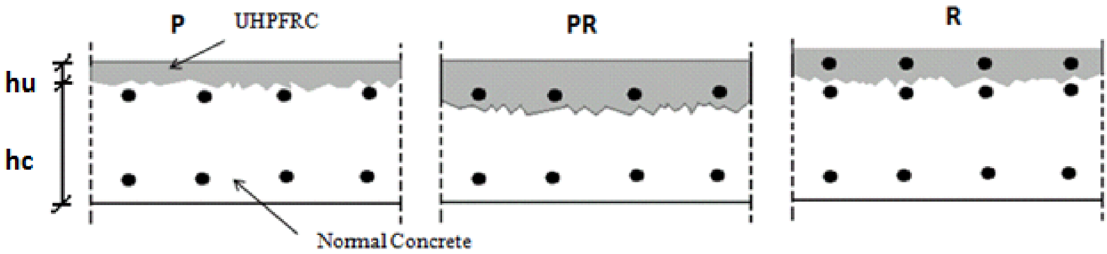


Figure 6.1 Configurations for rehabilitation of Concrete Elements with UHPFRC. Adapted from Habel et al. (2006)

The P configuration was designed for protection of the normal concrete. The thickness of the UHPFRC layer varies from 15 to 30 mm. Later on, experiments on P configuration showed that cracks in UHPFRC layers were formed at first 70% of the maximum moment with the UHPFRC layer on the tensile side, which proved its function of protection.

The PR configuration was designed for purpose of protection and rehabilitation of the structure. Corroded bars were replaced and a new layer with UHPFRC was applied. The height of the new layer near the top surface including reinforcement bars was around 50 mm. The maximum moment capacity increased and cracks appeared in the UHPFRC layer at 83% of the maximum moment.

The R configuration was designed for strengthening i.e. to increase the resistance and at the same time to protect the structure. It is stronger and stiffer than PR and P configurations. The thickness of the UHPFRC layer varies around 5cm. The rotation capacity was also reduced by adding extra reinforcements on tensile side. For more details on structural response of elements combining UHPFRC and Reinforced concrete see Habel *et al*., (2006).

6.1.1 SAMARIS (Sustainable and Advanced Materials for Road Infrastructures) European Project

In 2004, during the European project SAMARIS, UHPFRC was first applied for rehabilitation of existing concrete structures in Europe. A bridge over the river La Morge in Switzerland was rehabilitated and widened using UHPFRC of the $\text{CEMTEC}_{\text{multiscale}}^{®}$ family. The bridge had no water proofing membrane and the edge beams were severely damaged by chloride ingress. The bridge was rehabilitated in three steps. In the first step the bridge was widened by a prefabricated UHPFRC edge beam and a reinforced beam. Then, the existing concrete overlay and edge beam were replaced by a UHPFRC overlay and edge beam respectively, as shown in Figure 6.2.

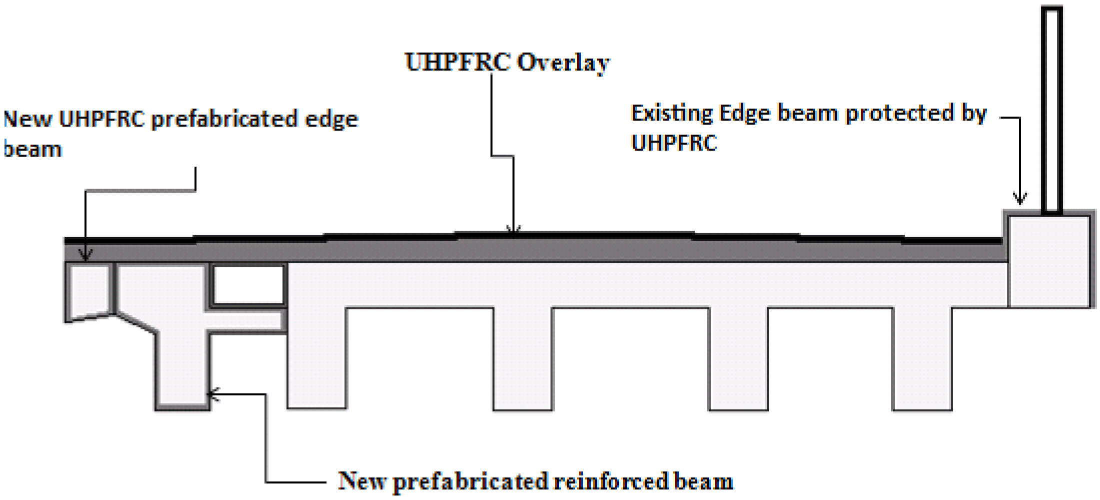


Figure 6.2 Cross Section of Bridge after rehabilitation with UHPFRC. Adapted from Denarié (2005).

The UHPFRC overlay was cast in two steps on two lanes of the bridge. The longitudinal joint was specially designed for transmission of tensile forces. To avoid any discontinuity UHPFRC was cast on site to cover both the kerb and reinforced concrete beam (Denarié, 2005).

The UHPFRC behavior was investigated after one winter-season and some corrosion spots were found on the exposed surfaces of the edge beams. An economical analysis was done by comparing three methods of intervention. The construction cost of the UHPFRC intervention was found not significantly higher than the traditional methods for rehabilitation of bridge decks and the time for construction activities and closing of traffic lanes could be reduced (Denarié, 2005).

6.1.2 Barrier (Parapet) wall of bridge

A barrier wall on a bridge deck is subjected to severe environmental exposures such as splashing of de-icing salts and also impact load from vehicles. However, when barrier walls are casted with UHPFRC, having low permeability and high ductility, they show excellent improvement of durability and mechanical properties (Oesterlee *et al*. 2006).

In 2006, a 3 cm layer of CEMTEC® was applied on a barrier wall. The mixture contained 6% of steel fibers by volume. Internal tensile stresses develop in the new layer due to early age shrinkage restrain by normal concrete. The UHPFRC layer was designed by using numerical analysis to resist these stresses (Oesterlee *et al*. 2006).

The UHPFRC was fabricated in a normal concrete mix plant, transported to site by a truck and poured into the tight formwork. Leakage in formwork may cost significant loss of material. In-situ air permeability and laboratory tests were conducted to confirm the high strength and low permeability of the UHPFRC layer. After four months no macro crack was developed in the layer (Oesterlee *et al*. 2006).

6.1.3 LOG ČEZOŠKI Bridge Slovenia

In July 2009, UHPFRC was applied for the first time for rehabilitation of a bridge deck over Šoka River in Slovenia. The bridge was 65m long having 5 % longitudinal slope. It was a great challenge for the Engineers to modify the mixes of UHPFRC to tolerate to a slope of 5%. Two recipes, one with thixotropic behavior and one with more fluid mix were used. The mechanical properties of the mixes were verified in the in-situ laboratory and through air permeability tests.

The old concrete surface was made rough to get a good bonding to the UHPFRC. The upper surface of bridge, the footpath and the external side of the edge beams were casted with UHPFRC in two days as shown in Figure 6.3.

The Application of UHPFRC on a bridge deck in Slovenia presented the solution for the various deterioration problems without increasing rehabilitation costs. Moreover, rehabilitation of the bridge with UHPFRC was found more sustainable based on CO_2 calculations (Denarié *et al*., 2009).

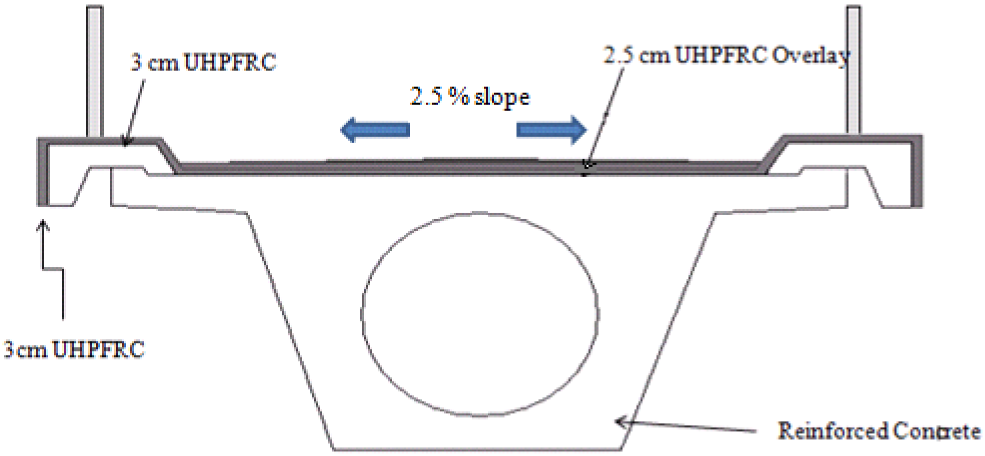


Figure 6.3 Cross section of bridge rehabilitated with UHPFRC. Adapted from Denarié et al. (2009).

6.1.4 Pinel Bridge, France

The two lane Pinel Bridge was constructed with ordinary concrete in 1996 in France. The bridge was 27 m long and 57 ° skew. Due to increase in traffic, the road authority wanted to extend the bridge to five lanes.

Initially it was suggested to use a filler beam deck with steel beams. But later the contractor Effiage TP proposed the innovative solution to use UHPFRC beams instead of filler beam deck. The main characteristics of the Effiage design are as follows.

The depth of the beams was 620 mm. Twenty eight prestressing strands were provided in the bottom flange and one in top flange. The beams and the slabs were connected by rebar stirrups extending from the top flange. Two cross beams were casted at the ends of the main beams to hold them together. The edited guide "Ultra High Performance Fiber Reinforced Concrete-Interim Recommendation" was used to check the beam design. The size of the web and the top flange of the external beams was increased by 3 cm as they were found to have too low strength with respect to shear. The beams were transported by trucks to the site and were placed on elastomeric bearings (Thibaux, 2008).

The Effiage design was less expensive than the other tenders. Furthermore construction of the beams were more stable, light weight, gave less disturbance to traffic and increased rapidity of work after beam errection; these were considered to be the main advantages of Effiage proposal (Thibaux, 2008).

6.2 New bridges constructed with UHPFRC

6.2.1 Experimental validation of a ribbed UHPFRC bridge deck in France

MIKTI is a French project focusing on composite bridges. At the Laboratoire Central des Ponts et Chaussées (LCPC) an experimental validation of a ribbed UHPFRC bridge deck is performed. The design was validated according to Association Francaise de Genie Civil (AFGC) and Service D'etudes Techniques des Routes et Autoroutes (SETRA). A UHPFRC ribbed slab has been supported by two longitudinal steel beams. This design is proposed for a 3 span bridge with two lanes each 3.5 meters wide. The total depth of ribbed slab is 0.38 meters with 0.05 m slab only. The ribbed slab is post-tensioned to ensure required strength. This experimental ribbed bridge deck was in agreement with respect to SLS and ULS (Toutlemonde *et al*, 2008).

6.2.2 Use of BCV® for bridge construction in France

In 2005, the n°34 overpass (PS34) is built with BCV® by the Vinci group France. The bridge is single span with total length of 47.4 meters. The slab is 3 meters wide and 14 cm thick and made up of prefabricated segments of UHPFRC. A prestressed box girder shape is adopted as a cross section for this bridge. The total height of the girder is 160 cm. There was no water tight layer used on the slab of this bridge because special type of formwork was used to insure proper surfacing and give adhesion to the vehicles too. There were no intermediate piers used (Resplendino, 2008)

6.2.3 Use of RESCON for bridge construction in Austria

A new Ultra High Performance Concrete called RESCON, made up of local materials in Austria, has been developed through the collaboration between SW Umweltteknik

Austria, Forschungsförderungsgesellschaft Austria (FFG), Graz University of Technology Austria and University of Kassel Germany. RESCON has a compressive strength of 195 MPa, bending strength from 17 MPa to 20 MPa, density of 2450 Kg/m^3 and modulus of elasticity E is 49 GPa (Monai & Schnabl, 2008).

In conventional bridge construction the part of the slab between the edge beam and main girder is heavy and bulky. They are constructed in-situ and require expensive formwork. These are replaced by construction of thin RESCON side layers. RESCON gives a better solution than Normal Concrete in terms of high resistance to chlorides attack, light weight, better workability, high strength and low life cycle cost. The side layers constructed of RESCON can be used as scaffoldings for the construction of Edge beams, parapet and shoulders (Monai & Schnabl, 2008).

RESCON can be used for the construction of pedestrian bridges which is an effective option. The maximum span length of the bridge is 20 meters with 3.5 meters deck width and plate thickness up to 10 centimeters. The geometry can be modified and adjusted according to use and topography which makes it very economical option (Monai & Schnabl, 2008).

6.2.4 Use of Ductal® for bridge construction in Canada

In 1997, a single lane pedestrian bridge was constructed across the Magog River, with the use of Ductal® as construction material in Quebec, Canada. The total length of the bridge is 60 meters divided into 6 segments with a space truss. Each segment is 10 meters long and 3 meters high precast structure. The top deck slab is only 30 mm thick giving one of the most slender bridge deck slab. No passive reinforcement is used in this bridge which makes it an attractive example for the validation of UHPFRC as effective and innovative construction material (Perry & Seibert, 2008).

Another single span pedestrian bridge was constructed across an 8- lane highway, with the use of Ductal® as construction material in Calgary, Alberta, Canada. The total length of the bridge is 53 meters. A deck 3.6 meters wide at the mid-span is resting on post tensioned girders. The girder is T-shaped with 33.6 meters length and 1.1 meter deep. Special type of passive reinforcement is used in which the bars are made up of glass fiber plastic. The abutments are also made up of UHPFRC. The T-shaped girder is a monolithic structure treated with heat of 90^{0}C to ensure required strength and durability. The use of Ductal® drop-in girders gives greater structural strength with reduced weight, quick installation, high resistance against chloride ingress, durability and superior aesthetics (Perry & Seibert, 2008).

6.2.5 US Highway Bridges

The Federal Highway Administration (FHWA) since 2001 has been investigating to produce light weight and more durable precast UHPFRC components. Various modular shapes of UHPFRC components have been developed and up till 2009, four bridges have been constructed using UHPFRC. FHWA is conducting the research on development of different structural sections of UHPFRC which can be efficiently deployed in highway bridges. e.g. π-Girders and Waffle Panels

Mars Hill Bridge

In 2006, Mars Hill Bridge Iowa was the first single span UHPFRC bridge open to traffic in U.S. The bridge comprises of three I-shape girders made of UHPFRC with a depth of 1.07m. Due to excellent mechanical properties of UHPFRC, it was possible to use prestressed I-girders with shallower flanges and narrower web instead of standard Iowa T-girders. Furthermore, the tests on the girder confirmed the efficient load carrying capacity of girder which eliminated the shear reinforcements from the web. However, to achieve the composite action between the deck and girder, hair pin reinforcements were casted in upper flange of girders (Graybeal, 2009).

Jakway Park Bridge

The Jakway Bridge was constructed using π-shape UHPFRC girders in Iowa in 2008. Three girders were used for the width of 7.6m in the middle span.

The π-girders are similar in cross section to double tee-girders except the dimensions were changed according to the longer spans in bridges. The depth of girder was 840mm including 105mm thick integral deck. The thickness of web was 81-89mm and contains sixteen strands for prestressing. A 133mm deep shear key was used to connect the components longitudinally. Other cross sectional properties of π-girder are as shown in Table 6.1 (Graybeal, 2009).

Table 6.1 Cross-sectional Properties of π-Girder

Cross Sectional Area	0.555m^2
Moment of inertia	44.01×10^{9}mm^4
Self Weight	1.390 Kg/m

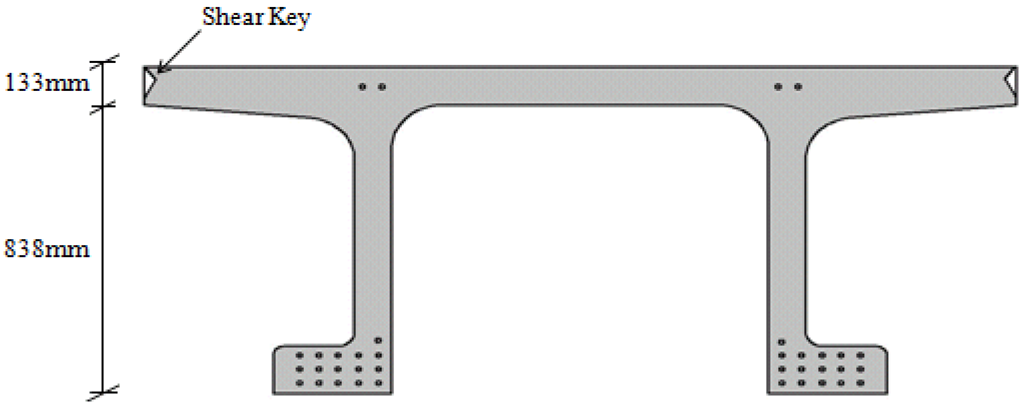


Figure 6.4 UHPFRC π-girder cross section. Adapted from Graybeal (2009)

Development of Waffle Panel

Due to safe and rapid construction and less hindrance to public the desire to use UHPFRC prefabricated bridge components is significantly increased. To fulfill the demand, LCPC (Laboratoire Central des Ponts et Chaussées) France investigated the use of UHPFRC in two way ribbed slabs (waffle slabs) instead of conventional concrete. After the analytical study, it was concluded that the cross section with 0.61m rib spacing with two 13mm prestressing strands in each rib has same flexural capacity as conventional deck panel. The waffle slab panels were first applied in Wapello County Bridge Iowa (Graybeal, 2009).

The height of ribs and thickness of slab may vary according to design requirement. Thickness of ribbed slab is designed to resist the bending and punching shear under concentrated wheel loads. While prestressed strands enhance the global bending capacity of the ribbed slab (Spasojević, 2008).

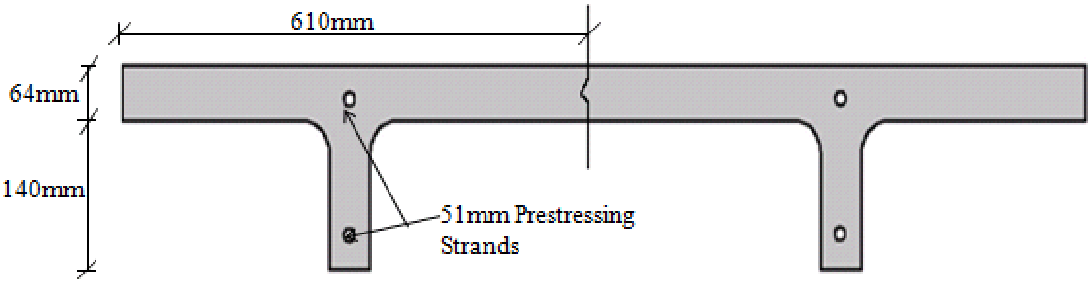


Figure 6.5 UHPFRC waffle slab cross section. Adapted from Graybeal (2009)

Bridge Connection Details

The connection between precast elements is always problematic and vulnerable to fatigue damage in bridge decks. Due to excellent mechanical properties, self consolidating nature and low permeability, UHPFRC has potential to connect the conventional precast elements. The six precast decks with UHPFRC as binding material were tested under cyclic loading. The results showed the optimal use of UHPFRC as a durable binding material in deck connections (Graybeal, 2009).

6.2.6 Shepherds Creek Road Bridge, NSW, Australia

In 2004, first application of UHPFRC of Ductal® family for highway traffic was completed in Australia. A single span timber bridge was replaced by concrete bridge. The bridge supports 4 lanes and 15m in length. The UHPFRC used in the bridge was fabricated in Australia with compressive strength of 200 MPa, flexural strength of 45 MPa and young's modulus of 47 GPa.

The superstructure of the bridge was constructed with precast Ductal® beams. The slab of the bridge was casted on Ductal® panels formwork between the beams which provide extra safety to bottom surface of slab. The weight of UHPFRC beams decreased to half of the weight of beams with conventional concrete. After completion of two lanes load tests on the bridge confirmed the design. Consequently in 2005, RTA (road Traffic Authority) proved the Ductal® to be used for roads and bridges in Australia (Rebentrost & Wight, 2008).

6.2.7 Papatoetoe Footbridge, New Zealand

The first Ductal® foot bridge constructed in New Zealand is 175m long, with 10 simply supported spans. Beams were fabricated in Australia in Ductal® plant. The beams have holes in the web and consist of 50mm thick slab. The deck slab is 2.2m wide and casted without conventional reinforcement. Ductal® due to its high compressive and tensile strength supports the deck slab. Furthermore, the Ductal® beams were significantly lighter than the beams with conventional concrete. The ribs spaced at 2.7m centre to centre. The strands were provided for post-tensioning under each rib and slab. The beams with Ductal® provide durable and lightweight engineering solution (Rebentrost & Wight, 2008).

6.2.8 Sakata-Mirai Foot bridge, Japan

The Sakata-Mirai Bridge is the first application of Ductal® in Japan. The deck slab was designed without passive reinforcement. The necessary strength was provided by Ductal® and external prestressing. The bridge is a single span and 50.2m in length. The bridge is cambered from the centre to satisfy the deflection criteria. The finite element analysis of bridge verified the design of the bridge. Two highway bridges were also constructed with Ductal® in 2005 and 2006 respectively (Rebentrost & Wight, 2008).

6.3 Life cycle cost analysis of UHPFRC bridge

In 2006, a single span highway bridge (Mars Hill Bridge) was constructed with the use of Ductal® as construction material in Wapello County, IOWA, USA. This bridge has been constructed of UHPFRC girders and cast-in-situ NSC deck and substructure (Ahlborn *et al*, 2008).

Here a case study has been done on two types of bridges to calculate the LCC of these bridges. First bridge is constructed of NSC girders, deck and abutments. Second bridge is constructed of UHPFRC girders and deck but NSC abutments (Ahlborn *et al*, 2008).

The NSC Bridge is single span with a total length of 33 meters and can accommodate two lanes of traffic. The NSC cast-in-situ deck is 7.5 meters wide and 0.23 meters thick. Three NSC precast prestressed I-beams are used as girders to support the deck. The design life of this bridge is 90 years (Ahlborn *et al*, 2008).

The UHPFRC Bridge is also a single span with total length of 33 meters and can accommodate two lanes of traffic. The UHPFRC precast deck is 7.5 meters wide and 0.10 meters thick. Three UHPFRC prestressed T-beams are used as girders to support the deck. The design life of this bridge is 180 years (Ahlborn *et al*, 2008).

The LCC analysis has been done in 2005-2006, according to RS Means Data and cross checked according to Michigan Engineers' Resource library (MERL). An inflation rate of 3% per year should be kept in mind for future calculations. For reference, the estimated cost of Mars Hill Bridge has been used which is $432,000 /-. Table XX shows the comparison of the LCC cost of NSC Bridge and UHPFRC Bridge (Ahlborn *et al*, 2008).

Table 5.6 Comparison of the LCC Analysis of NSC Bridge and UHPFRC Bridge Adapted from Ahlborn et al. (2008).

Activity	**NSC Bridge**	**UHPFRC Bridge**
Construction	$273,000 /-	$497,000 /-
Maintenance	$71,000 /-	$4,000 /-
Total	**$344,000 /-**	**$501,000 /-**

It can be seen from the Table 5.6 that NSC Bridge cost $344,000 /- per 90years, while UHPFRC Bridge cost $501,000 /- per 180 years. Apparently, NSC Bridge is still cheaper than UHPFRC Bridge for a life span of 180 years. The cost of NSC Bridge is $130 per cubic meter and that of UHPFRC Bridge is $2615 per cubic meter. It can be clearly seen that the cost of UHPFRC Bridge is 20 times greater than NSC Bridge. However, the traffic disturbance cost has not been included for yearly maintenance of NSC Bridge, and deck replacement time and traffic disturbance cost has also not been included in NSC Bridge. In addition, if the efficient cross section of UHPFRC Bridge is used and incorporate user cost and special benefits of UHPFRC is added in calculation then the UHPFRC Bridge cost can be reduced to 12.5 % per cubic meter (Ahlborn *et al*, 2008).

7 Case study- The Källösund Bridge

This section treats the bridge where damage has been found in the edge beams. The formation of cracks has been found in the edge beams. Moreover, the corrosion of reinforcements in the edge beams has also been observed. This lead to the spalling of concrete from edge beams. Investigations and test have been carried out to check the performance of the edge beams. It was found that the edge beams are failed to perform according to the design load and needs to be replaced.

A case study is done in this section to study the rehabilitation of the Källösund Bridge done in past years. Furthermore, a new solution for the rehabilitation of the Källösund Bridge by application of UHPFRC is also proposed.

7.1 Description of the bridge

The Källösund Bridge was constructed in 1958-1959 to connect the two islands Tjorn and Orust to the mainland near the west coast of Sweden. It is a prestressed, box-girder bridge constructed by the free cantilevering method. The total length of the bridge is 325 m divided in four spans have length of 50 m, 107 m, 107 m, and 50 m respectively. The bridge was constructed with cast in-situ concrete (Samuelsson, 2005).

Figure 7.1 The Källösund Bridge seen from Stenungsöns, west direction. (Plos et al ,2004)

The free width for the traffic is about 7.5 m with a slope of 2.5 %. The bridge deck slab is 7.5 m wide with a thickness of 200 mm. The bridge deck is about 34 m above the sea level and the bridge girder is supported by three piers and two abutments. The main box girders of the bridge were constructed in parts as free balancing cantilevers. The girders were then connected with each other by hinges. The height of the girders varies from 7.5 m at the piers to 1.6 m at the abutments. A cross section of the box girder is shown in Figure 7.2. The thickness of the bottom slab of the girder varies from 260 mm to 200 mm. The girder wall thickness is 450 mm (Samuelsson, 2005).

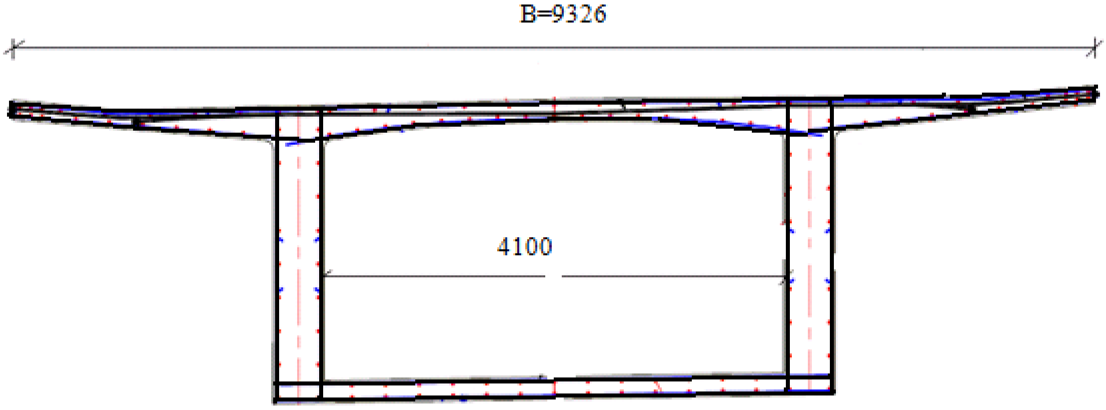


Figure 7.2 Cross Section of box-girder the Källösund Bridge. Adapted from Puurula (2004)

It was prestressed in both longitudinal and transversal direction with reinforcement of 26 mm in diameter. The main reinforcement in the bridge girders is prestressed. Most of the prestressing reinforcement was placed in the bridge deck slab, i.e. the top flange of the cantilevering bridge girders. The non prestressed reinforcements consist mainly of deformed bars of 10 mm diameter and of quality Ks40, i.e. ductile steel with characteristics yield strength slightly above 400 MPa (Samuelsson, 2005).

The concrete quality in the bridge girders corresponds to high quality bridge concrete of the time of construction with a characteristics compressive strength of approximately 40 MPa. The material and mechanical properties of the concrete were tested by the Swedish Road Administration in connection with the structural assessment and rehabilitation of the bridge (Samuelsson, 2005).

In 1982, a 2.5 m wide pedestrians and bicycle path (GC-path) was constructed along the southern side of the bridge. The GC-path was constructed of steel and was connected to the bridge girders using steel trusses (Samuelsson, 2005).

7.2 Damage detection and replacement of the edge beams

The expansion joints of the bridge have been rehabilitated twice, in 1982 and in 1993. The major problem observed was the 10 mm movement of the joints due to spalling out of concrete and cracks formation. Due to this large gap in the joints the chloride water passed in the deck slab and damaged the underside of the slab. In 1980's the splitting out of concrete cover was observed from the undersides of the edge beams. During the inspection in 1990 it was found that the entire northern part of the edge beams is damaged and also some parts in the southern side are damaged. In 2002, thorough observations showed that both the edge beams are damaged along its entire length. In 2003 and 2004, the damaged edge beams have been replaced by new one (Samuelsson, 2005).

Here the process of the replacement of the eastern part of the southern edge beam has been presented. The damaged edge beam was removed in a systematic way. A high pressure water blower was used to remove the damaged edge beam so that the transversal reinforcement can be preserved. Then the part of the deck slab adjacent to edge beam was cleaned off, of the loose concrete particles and was watered. The damaged edge beam was replaced with a new one. The casting of concrete was done in successive segments of 8 m length. The concept of segmental casting was adopted, to accommodate any elongation during hardening of fresh concrete. Strain gauges were installed in the edge beams at different positions to measure any elongation occurred. The casting was initiated from the middle of the end span towards the Stenungsöns abutment. An 8 meter segment was cast in week 41 followed by another 8 m segment in week 42. In week 43 the remaining part was casted. The edge beam casting was done in two different cooling conditions to observe the effect of temperature. First the non cooling casting was done followed by the cooling casting. A cooling pipe was used in the casting of edge beam to reduce the risk of temperature cracks. The temperature of the cooling water inside the pipe was maintained between 8 to 15°C. The type of concrete used was C35/45 with water cement ratio of 0.4 (Samuelsson, 2005).

While the concrete was getting hard, the temperature development was noted down at different sections after an interval of 10 minutes, both for the cooled casted part and non cooled casted part. ConReg 706 was used as data logger for middle sections and SwemaLogg 15 was used for edge sections and the sections between cold water and deck slab (Samuelsson, 2005).

The deformation was recorded at different sections by using the strain gauges. The total deformation recorded is the sum of temperature deformation, stress induced strain and shrinkage (Samuelsson, 2005).

The restraint stresses produced in the cooling part were 1.21 MPa and 2.11 MPa in the non cooling part. This clearly shows that the cooling has positive effect in the hardening process and reduces the risk of cracks. However, after three months, cracks were observed in the parts of the edge beam (Samuelsson, 2005).

7.3 Rehabilitation alternative with UHPFRC

Only after 3 months cracks were observed in parts of the edge beam again. Therefore, an alternative solution is presented here focussing on the potentials of UHPFRC.

The recipe of UHPFRC use for rehabilitation should full fill following goals. The UHPFRC mix should have very low permeability to fluids and gases and shouldn't show macro cracking. The mix should show excellent mechanical performance and self compacting character. Denarié (2009), project has provided some guidelines in selection of UHPFRC recipe for the rehabilitation purpose. The UHPFRC prefabricated elements with 2% fibers volume are sufficient to be use in the case where there is less hindrance to early age shrinkage and bending behaviour is dominant. In case of cast on site as UHPFRC overlays, where existing structure restraint the early age shrinkage of new matrix. Consequently, the tensile stresses produce in the matrix. To accommodate these stresses the matrix must exhibit tensile hardening response for which high dosage of fibers up to 6-9% by volume will be sufficient (Denarié, 2009).

Due to the above mentioned mechanical and long term durable properties of UHPFRC, the edge beams will be constructed by UHPFRC. Furthermore, overlay of UHPFRC will be provided over the whole width of bridge deck.

7.3.1 Composition of UHPFRC

During the ARCHES project two new recipes of CEMTEC$_{\text{multiscale}}$$^{®}$ with new matrices with different rheological properties were developed in Slovenia. The basic properties of the both recipes were same as CM23 recipe used in the rehabilitation of La Morge Bridge in 2004. However, limestone filler reduced the amount of cement from the 1434 kg/m^3 to 763 kg/m^3. Their water/ (cement + limestone) was 0.170. The component details of both recipes are shown in Table 7.2.

Table 7.2 Composition of CEMTEC$_{multiscale}$$^{®}$ recipes (Denarié et al., 2009)

Components	CM32_11	CM32_13
Cement	763 kg/m^3	763 kg/m^3
Limestone (filler)	763 kg/m^3	763 kg/m^3
Micro Fibers	L =1 mm	L =1 mm
Macro fibers	L_f =10 mm	L_f =10 mm
Slope tolerance	Limited	High

The CM32_13 recipe was designed with addition of a thixotropizing agent SIKA Extender$^{®}$, as result it can tolerate slope up to 5%. These recipes were prepared and applied for the first time in 2009, for the rehabilitation of LOG ČEZOŠKI Bridge Slovenia. The mixing time for materials was 12 minutes and no segregation was reported. Further test on workability over 2 hours intervals showed no significant loss of slump (Denarié, 2009).

7.3.2 Application of UHPFRC

UHPFRC is a relatively expensive material and it should be applied to structures subjected to severe environmental conditions and where more resistance is required without increasing the dead load of the structure. The less exposed and loaded parts of the structure are built of NSC.

The surface of the existing concrete is made rough with hydro-jetting before the application of the UHPFRC to ensure good bonding between the two layers. The cross section of the bridge after rehabilitation is shown in Figure 7.3 and Figure 7.4. The edge beams and overlay of the deck slab will be monolithically cast on site with UHPFRC. There is no slope tolerance required for edge beam so it will be casted by recipe CM32_11. However, slope is required for water drainage over the bridge deck. Therefore overlay will be casted with recipe CM32_13.

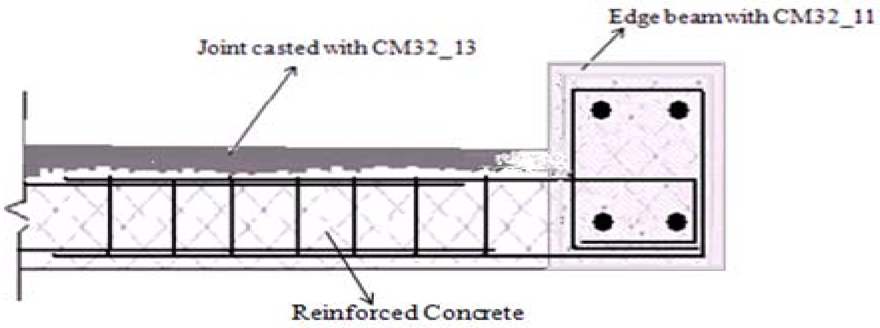


Figure 7.3 Proposed Cross Section of Edge beam and overlay casted with UHPFRC

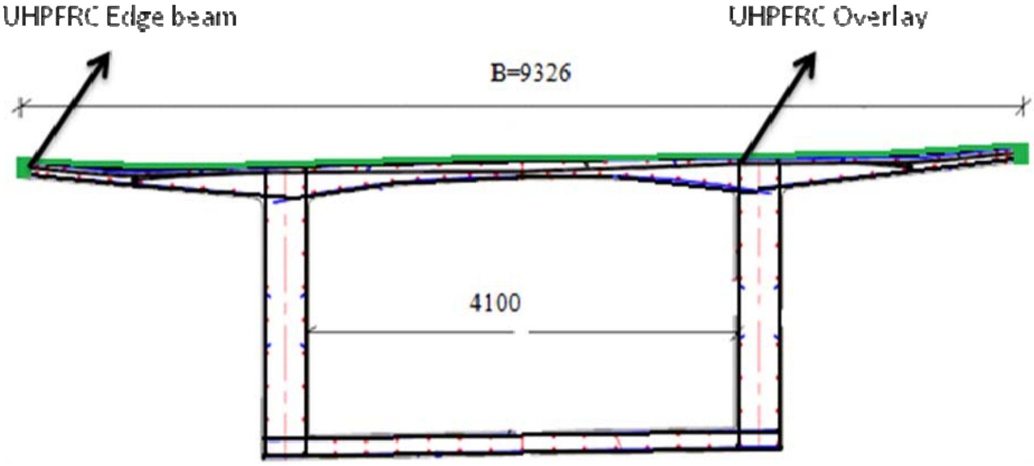


Figure 7.4 Cross section of Bridge after Rehabilitation with UHPFRC

A significant traffic passes over the bridge every day. Therefore, UHPFRC will be casted in two steps on almost 10 m wide deck. In first step overlay will be casted over one lane will be continuously moist cured. When the overlay will get enough strength, this lane will be open to traffic. Similarly in second step other lane will be casted with

UHPFRC overlay. The overlay will be casted continuously to expansion joints in such a way to avoid transverse dry joints. However, longitudinal joints between two layers will be specially designed to transfer the tensile forces between two layers. Typical longitudinal joint between UHPFRC layers was first applied during ARCHES project for the rehabilitation of Log Čezsoški bridge Slovenia as shown in Figure 7.5.

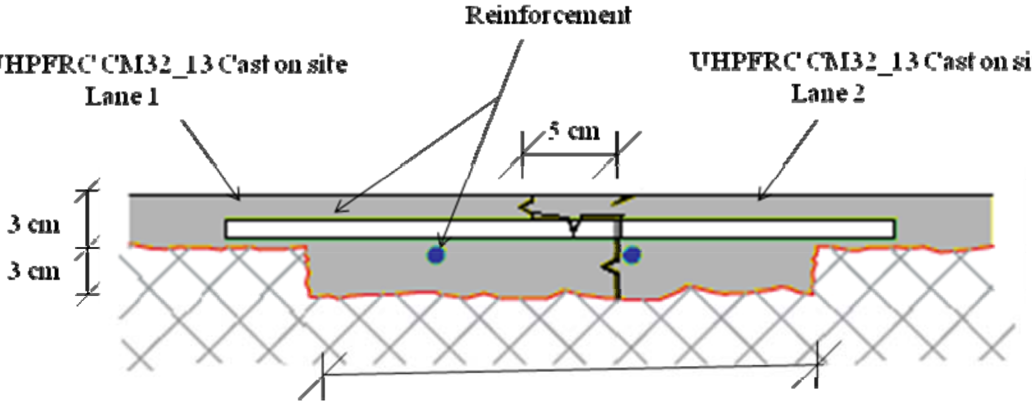


Figure 7.5 Details of Longitudinal joint between UHPFRC layers. Adapted from Denarié et al. (2009)

7.3.1 Environmental impact

Every human being needs comfort, satisfaction and happiness. Since the very beginning of human kind, struggles have been done to achieve these basic needs of life. With the passage of time research and development has been done to get more and more products from the available resources. Enormous development has been done till now, as a result the world is becoming more and more industrial and chemical instead of natural. It is very important for the world, to develop and become more and more prosperous.

However, the development has lead to certain reversible and irreversible problems in the nature such as CO_2 emissions, population increase, agriculture decrease, and chemical increase, and ozone layer disturbance, landscape degradation, forestry decrease, acid rains, and wastage of energy, inefficient use of energy etc. Therefore, efforts should be made to stop this disturbance of the natural system. However, it is not logical to stop the development of human being. Alternatively, struggle has to be made to effectively use this development for the betterment of human kind. Energy should be used to assure the need of human kind and also to save energy for future. Chemical industry should progress more and more keeping in view the natural safety and preservations. Therefore environmental problems should be addressed with systematic approach. Furthermore a sustainable development pathway should be adopted (Denarié *et al*, 2005).

The building materials sector is one of the largest CO_2 emission sectors, of which concrete structures contribute the largest share. Due to industrialization an enormous amount of available natural resources are used for development. In the past few decades the demand of natural resources has been significantly increased. The environmental disorder is one of the key problems that the world is facing for the last few decades. People from every scope of life are trying to address this serious issue within their own capacity (Denarié *et al*, 2005).

Due to this ideology of rehabilitation system, which consumes fewer materials and emits less CO_2 have to be developed. The sustainability study during ARCHES project based on CO_2 calculation showed that application of UHPFRC with 50% limestone filler is most sustainable rehabilitation system as compared to other standard system for rehabilitation. Past experiences of rehabilitation of bridges with UHPFRC showed the fewer disturbances to the traffic than the standard rehabilitation systems (Denarié *et al*, 2005).

7.4 Comparison of the two alternatives

The average daily traffic on Källösund Bridge is 15500 vehicles (ADT). It is a very expensive job to rehabilitate the bridge after a short time. The Swedish Road Administration spends a huge amount of money on rehabilitation of bridges every year. Therefore, the bridge is rehabilitated with UHPFRC in the proposed solution.

Ultra High Performance Fiber Reinforced Concrete (UHPFRC) is characterized by a unique combination of extremely low permeability, high strength and deformation capacity. During the SAMARIS project UHPFRC have been applied for the rehabilitation of bridges. The application of UHPFRC on bridges has demonstrated that it gives a good solution for cast in-situ rehabilitation by using standard equipment. The hardening of UHPFRC requires less time than NSC thus the traffic disturbance time can be reduced to a considerable level. Due to fast and efficient rehabilitation by using UHPFRC the Life Cycle Cost can be reduced further. Furthermore, no waterproofing membrane is needed when using UHPFRC. Thus, the bituminous concrete can be applied after only 8 days of moist curing of the UHPFRC instead of the usual 3 weeks of moist curing of NSC. Due to high abrasion resistance of UHPFRC, it is proposed that it can be used without bituminous concrete even. The sustainability study during ARCHES project based on CO_2 calculation showed that application of UHPFRC with 50% limestone filler is most sustainable rehabilitation system as compared to other standard system for rehabilitation. Also, the durability of UHPFRC is much higher than usual concretes (Weirzbicki, 2010).

8 Case Study: Bridge over Tolångaån

Composite bridges have become a reliable and popular solution in many countries. Steel girders are provided to support a concrete deck slab. The deck slab is connected to the steel girders by shear connectors or headed studs. For more details on joints between steel girders and prefabricated slab elements see Collin *et al*. (2002).

One of the advantages of composite bridge construction is that steel beam can carry the weight of the wet concrete during casting; therefore no extra temporary structure is required. Also the construction time for the bridge reduces, which may save money particularly during winter time in cold countries. Moreover, casting of bridge deck slabs with prefabricated elements is an even faster way of construction. But one of the main problems in prefabricated elements is how to cast the joint between prefabricated elements as joints are normally the weakest part in the construction (Collin *et al*. 2002).

In Sweden, the bridges have mostly cast-in-situ bridge deck slabs using normal strength concrete as construction material.

8.1 Description of the bridge

Here a case study has been presented of a bridge located in Sweden. The bro M 1255 Tolångaån is located in Sjöbo, Skåne, Sweden. The longitudinal structural system is a bridge deck supported on both sides by two abutments. The supports are hinge supports which allow horizontal movement. A bridge deck slab supported on two girders is the main structural system. The slab is cast-in-situ NSC with two steel girders. The total length of the bridge is 30.80 meters. The total width of the deck is 8 meters (Trafikverket, 2000).

The load case used is according to BRO 94 PUBL. 1994:2 as shown in the Figure 8.1 below (Trafikverket, 2000).

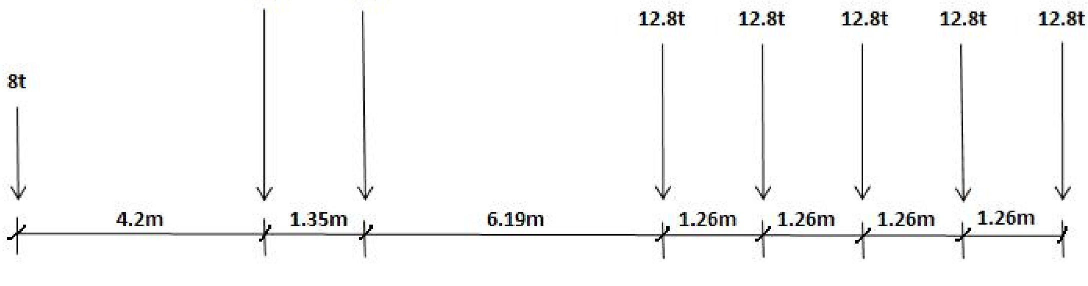


Figure 8.1 Load case BRO 94 PUBL. 1994:2. Adapted from (Trafikverket, 2000).

The deck slab is spanned transversely between two girders and cantilever transversely at the outer sides of the girders. The deck slab is 6.5 meters wide having a gradient of 2.5%. The deck slab is 310 mm thick at the centre and 210 mm thick at the edges near the edge beams. The K45 strength class concrete is used for the construction of cast-in-situ bridge deck slab. Water cement ratio used is 0.45. The type of reinforcement used is Ks60. The concrete cover used is 100 mm (Trafikverket, 2000).

Normal strength concrete is C30/37 with f_{ck} 30 MPa, f_{ctm} 2.9 MPa and E_{cm} 32 GPa

Height of the girder is 1065 mm with upper flange smaller than the lower flange. Composite action is achieved between the slab and the girders by using two connectors at the top flange of the girder. The two girders used to distribute the traffic load are spaced 4 m. It also transfers the vertical load from the traffic to the abutments (Trafikverket, 2000).

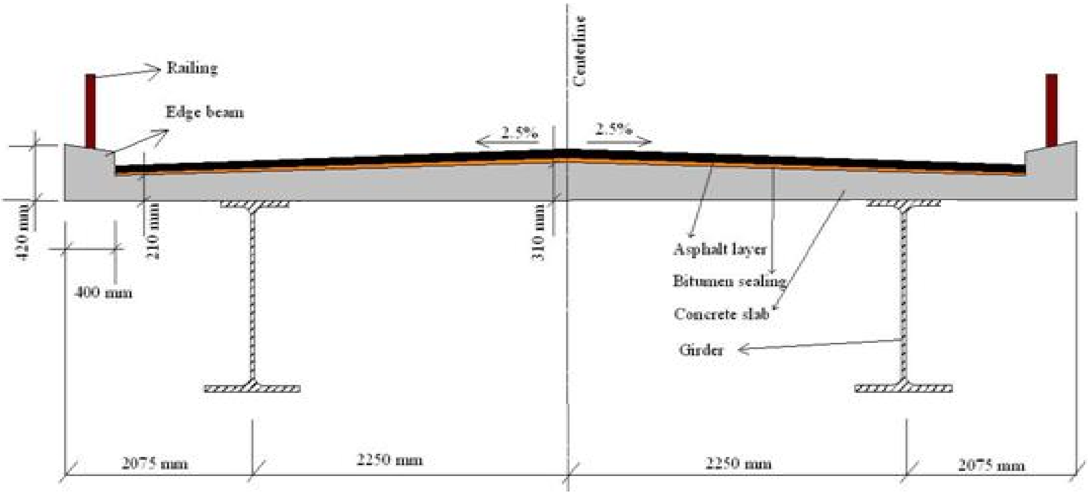


Figure 8.2 Bridge deck slab cross section constructed with NSC. Adapted from (Trafikverket, 2000).

Edge beams having 400×420 mm dimension are provided at the edges of the deck slab. The K40 strength class concrete is used as construction material for edge beams. The reinforcement used is Ks60 (Trafikverket, 2000).

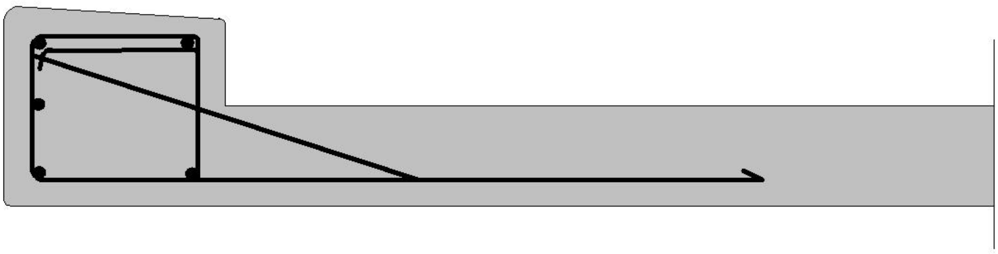


Figure 8.3 Edge beam detailing. Adapted from (Trafikverket, 2000).

8.2 Bridge alternative with prefabricated bridge deck slabs and UHPFRC

In this section application of UHPFRC for construction of a bridge deck slab of composite bridge is proposed. The bridge deck slab is constructed with precast normal strength concrete elements.

8.2.1 Description of the bridge

Here application of UHPFRC for the construction of a new bridge is presented. The bridge description is same as explained in section 8.1 but bridge deck slab is considered as precast in this case.

The bridge deck slab is supported over steel beams. The cross section and connection of these beams with prefabricated deck slab will be chosen according to the design requirements in Eurocode. The bridge deck slab and edge beams are constructed with precast normal strength concrete. Precast elements of slab are connected together by UHPFRC joints. An overlay of UHPFRC is laid over the whole bridge including edge beam see Figure 8.4. The properties of NSC and reinforcement for the pre-cast slab will be selected according to the design specifications of the bridge. In case of cast in situ overlay, early age shrinkage of UHPFRC layer will be restrained which will develop tensile stresses in the new overlay. To overcome these stresses and obtain the delayed micro cracking even ultimate strength of matrix is reached, the UHPFRC must exhibit strain hardening. (For more details on restrain stresses read Habel, 2008). For this, UHPFRC needs less dispersion of mechanical properties due to fibrous mix. Many UHPFRC recipes are under development in the world. Very few recipes can satisfy at same time low permeability, strain hardening, high tensile and compression stress and self compacting behavior. The recipes developed using lime filler as replacement of unhydrated cement were found more suitable recipes which improved workability without compromising the strength of the matrix. In addition the slope tolerance of specific recipes was enhanced for cast in-situ application with slopes 3 to 5%. These recipes are CM32_11 and CM32_13. The composition of these recipes is given in Table 7.2. Moreover, the recipes can be made very easily worldwide (Denarié *et al.*, 2009). The bituminous concrete layer will be used over the UHPFRC layer to provide slope of 2.5% to both sides from centre for the drainage of water.

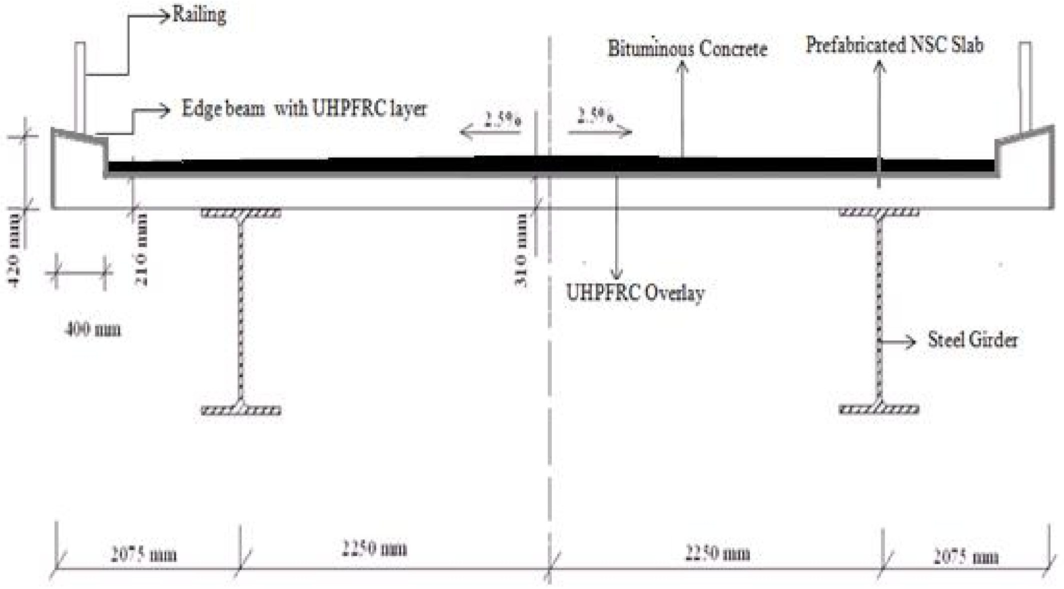


Figure 8.4 Proposed cross section of the composite bridge deck with NSC prefabricated Slab and UHPFRC Overlay

8.2.2 Joints Details

Joints are used as to connect two pieces of concrete together and to transfer the forces acting on them. Generally joints can be classified into two types. In first type, the joints can transfer the moments. While, in 2nd type joints cannot transfer the moments. Joints of first type develop a continuous structure with adjacent prefabricated elements. Therefore these types of joints are more preferred.

Since structural behavior of prefabricated elements is mainly govern by the joints between them. Therefore, detailing of these joints is one of the main issues to provide best performance in regard to efficiency. Prefabricated decks slabs are usually precasted with the same length as width of the bridge deck and their width is usually less than 2 m (Harryson, 2008). Consequently, with conventional joints it becomes more complicated as they involve loop bars and more transverse reinforcements as show in the Figure 8.5 (a). However, there is still need for new joints which are easy and fast to perform, and which makes the surrounding prefabricated elements continuous Model code 1990 provides some guidelines about easy and quick installation of the joints between prefabricated elements. (Harryson, 2008)

In 2008, Peter Harryson presented idea of casting of joints between prefabricated elements with UHPFRC. The aim of his work was to design a joint which is easy to install and perform better. Therefore, new joint 100 mm wide, with simple reinforcement detail was casted with CRC having water/binder ratio of about 0.16. Furthermore, these joints were tested for fatigue, shear and bending capacity in Chalmers University of Technology. The results showed that the joints become much stronger than the connecting parts if proper detailing of lap length is provided which was almost equal to 80mm. Moreover, the transverse reinforcement enhances the ductile behavior of the joint. For more details on tests on connection between prefabricated slabs casted with UHPFRC see (Harryson, 2008)

In this case, prefabricated joints are casted with CM32_11 as there is no slope requirement. The mechanical and durability properties of CM32_11 are almost similar to CRC except the composition of recipes. Despite this CM32_11 has significant tensile capacity to resist the retraining forces. Also it can be easily prepare in all over the world. The splice length of the reinforcement is equal to the width of the joint i.e. 100 mm as shown in Figure 8.5 (b).

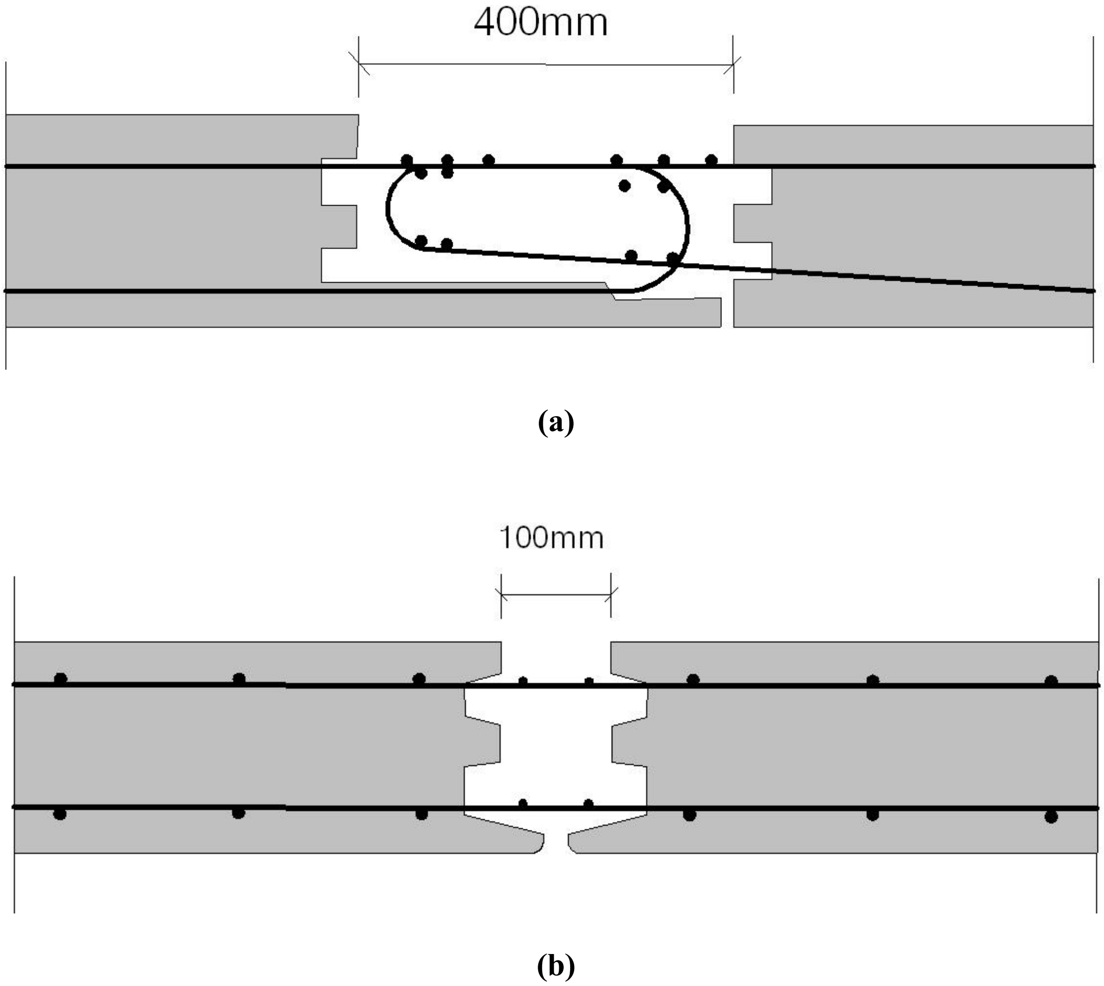


Figure 8.5 Joint between Prefabricated Slab casted with (a) Normal strength concrete (b) UHPFRC. Adapted from Harryson (2008).

8.2.3 Application of UHPFRC overlay

After casting the connections between prefabricated deck slabs, a continuous 2.5 cm UHPFRC overlay of recipe CM32_13 with no dry joint is applied over upper face of bridge deck and edge beam. Despite this, sides of the edge beam are casted with recipe CM32_11 as no slope tolerance required. Formwork is used for casting of these layers of edge beam. However, formwork has to remain open from lower side to guarantee the continuity of the overlay over edge beam and upper face of deck without any dry joint as shown in figure 8.4. The stiffness of the composite slab is significantly improved by the application of 2.5 cm thick UHPFRC layer.

8.2.4 Comparison of bridge deck alternatives

A case study was done to study the comparisons between the bridge deck slab constructed on site with normal strength and prefabricated slab with UHPFRC joints and overlay.

In first case bridge deck slab is casted on site with normal strength concrete and supported by steel girders. Structures built with normal strength concrete performs very well in most applications but still lacks durability under severe environmental conditions.

In second case the bridge deck slab was constructed with precast elements and the study on joints casted with UHPFRC revealed that joints can be made stronger than the surrounding prefabricated elements by proper detailing and providing sufficient lap length for reinforcement. An overlay of 2.5 cm thick of UHPFRC is casted for protection purpose over the bridge deck slab according to the design configuration presented by Habel, 2004. The overlay acts as water tight membrane and resists the penetration of salts into concrete and makes the slab more stiff, thus increases the service life of the bridge deck. But life cycle cost in this case will be higher than the cast in-situ bridge deck slab as shown in section 6.4. However, the duration of the construction works and closing of traffic lanes could be largely reduced.

9 Conclusions

In this thesis a study was done to investigate the problems related to bridge deck slabs. Bridge decks are constantly subjected to traffic loads and are exposed to environmental actions. Consequently they deteriorate faster than the other parts of the bridge. The use of de-icing salts leads to chloride penetration and corrosion of steel reinforcement.

The major maintenance problem for concrete bridges is corrosion of reinforcement. The corrosion of reinforcement can be controlled by improved protection of the reinforcement through cathodic protection, protective reinforcement coating or non corrosive reinforcement material. An alternative is to have an impermeable and uncracked concrete cover. One way to obtained this is by using Ultra High Performance Fiber Reinforced Concrete (UHPFRC).

UHPFRC has shown high very high compressive strength (more than 160 MPa) and large tensile strength (more than 8 MPa), along with strain hardening behaviour which ensures the formation of multiple micro-cracks and keeps the crack width small. However, fiber orientation and casting techniques significantly affects the mechanical properties of UHPFRC. The UHPFRC has been found to be more resistant to chloride attack, freeze-thaw attack, alkali aggregate attack and abrasion in durability studies conducted by various researchers. Strain hardening is an essential property of UHPFRC since it keeps it less permeable even after crack initiation. Therefore, an overlay of UHPFRC shows better resistance against aggressive environmental effects and increases the service life of bridge deck slabs.

Successful rehabilitation of bridge deck slabs is a major issue. When a new layer of UHPFRC is applied over the existing concrete structure, a new composite structure is formed. Eigen stresses are produced in the new layer due to restrained shrinkage. Due to both deformability and strain hardening behaviour, the intensity of induced stresses is reduced.

UHPFRC has been applied to several bridges, both for rehabilitation and construction of new bridges. A sustainability study during the ARCHES project based on CO_2 calculation showed that application of UHPFRC with 50% limestone filler was the most sustainable rehabilitation system compared to other standard system for rehabilitation.

The effect of using UHPFRC was studied in two case studies, in which the rehabilitation of an old bridge and the construction of a new bridge were compared to UHPFRC alternatives. The concept of application of UHPFRC was to use it where the structure is more exposed to severe environment actions and high traffic loads. This conceptual idea significantly improves the durability and decreases life cycle costs of both rehabilitated and new concrete structure.

Application of UHPFRC also reduces the layer thickness in case of rehabilitation and increases the capacity of structure without increasing deadweight.

UHPFRC also reduces the duration of rehabilitation works; traffic lanes can be open after few days. In addition, if the efficient cross section of UHPFRC bridge is taken into account and the user cost and special benefits of UHPFRC is added in the calculation, the bridge deck cost can be reduced by approximately 10 %.

The application of UHPFRC in the composite bridge construction with prefabricated elements enhance the service life of the bridge deck slab by providing stronger joints between the prefabricated bridge deck elements and by applying a non-permeable UHPFRC overlay on the bridge deck slab.

A major advantage of prefabricated construction is shorter construction time. Prefabricated concrete members have potential to be more durable than the cast in-situ concrete if they are made in controlled construction environment in factory. However initially more investment is required for plant machinery in case of prefabrication of concrete, but this investment is often economical over time.

10 Further Studies

Deterioration of bridge deck slabs is a widely used subject for research since many decades. A large amount of investigations have been found in literature throughout the world. In this thesis an effort has been done using UHPFRC, to improve the performance of bridge deck slabs with respect to severe environmental conditions and traffic load. However, UHPFRC being relatively a new construction material requires further studies to be used as construction material for rehabilitation of bridges as well as for construction of new bridges. Application of UHPFRC to bridge deck slabs should be studied through laboratory tests as well as on-site tests to ensure the reliability. Here are a few suggestions for further studies;

- Structural behaviour of composite action of UHPFRC and NSC.
- Structural response of UHPFRC with conventional reinforcement.
- Detail research is needed to develop more efficient cross sections of bridge decks using UHPFRC.
- Detail Design Guidelines of fracture mechanics of UHPFRC needed to develop.
- Fatigue properties need to be further investigated.
- Research should be expanded in the areas of design optimization of manufacturing. In particular, faster and more economically efficient production methods need to be investigated. Also, by developing a design approach that expects a longer service life and less maintenance costs.

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