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Review

Application of Ultra-High Performance Concrete in bridge engineering

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HIGHLIGHTS

- Forty-two typical and practical applications of UHPC in bridges are introduced.
- The shortcomings which constrain the application of UHPC are summarized.
- Potential usages of UHPC for seismic resistance and anti-explosion are predicted.
- Further researches of UHPC in bridge engineering are proposed.

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ABSTRACT

Ultra high performance concrete (UHPC) is a type of cement-based composite, which is the most innovative product in concrete technology during the last 30 years. The advantages of UHPC compared with the common concrete, such as superior mechanical performance, excellent anti-seismic property and resistance against environmental degradation are introduced in the paper. The paper begins by briefly introducing its history of development and technical performance. Then, the research and application situation of UHPC in bridge engineering are discussed and many practical applications in bridge bearing component, bridge deck pavement and bridge joints are summarized. Moreover, the paper analyzes advantages and shortcomings of UHPC and the constraints for the application of UHPC in bridge engineering. In addition, the performance of UHPC in seismic resistance and anti-explosion is briefly summarized. Based on these works, prediction of UHPC further research in the future is prospected.

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1. Introduction

Ultra-High Performance Concrete (UHPC) is one of the most innovative cement-based structural engineering materials developed in the last 30 years from the perspective of mechanical properties and durability of concrete construction.

As early as 1930, Andresen and Andressen established the mathematical model of the maximum packing density theory. However, the first generation of UHPC designed by the model, called CRC (Compact Reinforced Composite), was born in Aalborg, Denmark until the development of superplasticizer became mature. CRC used sintered bauxite as aggregate, and steel fiber was mixed to improve the material's toughness. Influenced by the performance of superplasticizer at that time, CRC or early UHPC was difficult to achieve satisfactory uniformity by vibration for its viscosity.

At the beginning of this century, "UHPC" was defined for the first time in Europe. With the improvement of design principles and the introduction of ultra-efficient superplasticizer (Polycarboxylic acid), UHPC has a common concrete construction performance in self-compacting compared with the earlier CRC or RPC.

1.1. Development of UHPC

Concrete is a cement-based composite material and a hydraulic binder which is formed by combining cement with various aggregates. The structures developed in a higher, larger, deeper direction since the 20th century; therefore, stricter requirements on materials have been placed. In this case, the High Strength Concrete (HSC) with strength exceeding 60 MPa appeared in the late 1970s then and was widely used at that time [1].

Reactive Powder Concrete (RPC) is one of the most typical UHPC, which was first developed in 1993 at the Bouygues Laboratory in France. Its compressive strength is more than 150 MPa. and RPC is divided into two grades, RPC200 (strength below 200 MPa) and RPC800 (strength from 200 MPa to 800 MPa) [2,3].On the basis of the principle of preparation of RPC, experts from various countries have carried out new UHPC research, but the challenge to improve tensile properties of UHPC still remains. In this case, a fiber-reinforced approach was introduced to achieve a higher tensile strength.

In 2009, at the "Ultra-High Performance Fiber Reinforced Concrete International Conference" held in Marseille, France, it was noted that UHPC would have a new application in environmental protection and super durable performance [4].

1.2. Preparation of UHPC

The material components of UHPC consist of: (1) cement (2) well-graded fine sand (3) quartz sand (4) silica fume and other mineral admixtures (5) steel fiber (6) superplasticizer. The removal of coarse aggregate can improve the homogeneity and the internal structure of UHPC. The high density of UHPC is improved using well-graded fine sand, quartz sand and silica fume, which can reduce the porosity of the UHPC. In addition, the steel fiber has a different tensile stress, which effectively slows down the occurrence of concrete cracks. In order to reduce the amount of water and increase the strength, a large amount of effective superplasticizer is added, but the dosage should be taken care to avoid the retardation of the concrete.

Many scholars have done a lot of research on material components of UHPC. Nancy A [5] studied the possibility of producing and using glass sand (GS) for partial or total replacement of quartz sand in UHPC. Collepardi et al. [6] reported the effect of nano-Si02 on the properties of self-compacting concrete. It was found that nano-Si02 not only improved the cohesion of fresh cement paste, but also improved the mechanical properties and durability of hardened cement paste.

Mixture ratio of UHPC has been one of important research topics. Different regions in the world have their own unique features in water quality, cement, silicon ash and other mixtures, steel fibers may vary due to the high and low level of preparation technology. Furthermore, the environment in different areas may also influence the optimal mixture ratio of UHPC. Therefore, in order to obtain the ideal UHPC material performance, it is necessary to determine the best mixture ratio through experiments in different regions and to avoid directly using the existing proportioning data. This issue may be one of the most important factors that restrict wide applications of UHPC in bridge engineering. Table 1 gives the common mix of UHPC.

Curing temperature also has an impact on the performance of UHPC materials. There are three kinds of commonly used curing methods: room temperature curing, around 90 °C high temperature curing and steam curing at 200 °C. In general, strength of UHPC under the room temperature curing is 10%–30% lower than that of 90 °C high temperature curing. The steam curing above

Table 1
Mix proportion of UHPC.

Material	Cement	Silica Fume	Quartz Powder	Fine Sand	Steel Fiber	Accelerator	Water
Mass Ratio	28.5%	9.3%	8.5%	41%	6.3%	1.2%	5.2%

200 °C can obtain higher strength, but the first two curing methods are generally used due to limited equipment [7].

1.3. Material properties of UHPC

Compared with common concrete, UHPC has many advantages. Those including mechanical properties and durability are briefly explained in the following.

1.3.1. Compressive properties

The advantages of UHPC concrete in mechanical properties are mainly reflected in the compression. Although the steel fiber content and the curing conditions have an impact on their strength, its ultimate compressive strength can be basically maintained at more than 100 MPa [8]. UHPC uniaxial compressive strength of the test can reach 176.9 MPa, which is accordant to analysis of numerical simulation. Many studies have actively explored the UHPC matching scheme in accordance with regional conditions. In China, the ultimate compressive strength of 170.3 MPa has been achieved in the case of adding coarse aggregate materials [9].

The main factors influencing the compressive strength of UHPC are: steam pressure condition, curing time, fiber content, sample geometry size, loading rate, etc. Graybeal [10] presented the compressive strength of UHPC under different conditions by a large number of experiments and the following Table 2 is summarized.

The average compressive strength of UHPC is still significantly higher than that of common concrete under untreated conditions, and the compressive strength of UHPC is improved by autoclaving. It can be seen that steam curing has a very important effect on the formation of UHPC strength. However, in the actual application process, high-temperature curing is difficult to achieve, and the use of normal temperature curing is faced with the waste of material strength. Therefore, how to prepare UHPC with sufficient strength under the condition of curing at room temperature has a great influence on the popularization and application of UHPC.

1.3.2. Tensile properties

The tensile properties of concrete are generally not considered in bridge construction. However, the UHPC can improve the tensile strength with the steel fiber, and the UHPC can still maintain some tensile stress after cracking.

Studies have shown that when the steel fiber content is controlled under about 3% in weight, the tensile strength and flexural strength of UHPC are directly proportional to the content of steel fibers [11], and the effect of steel fiber content on the strength of the material is obvious. Different types of steel fibers can also affect the tensile performance of UHPC. Furthermore, the end hook steel fibers are more advantageous than other types of steel fibers [12]. The incorporation of steel fiber increases the fracture energy of UHPC and greatly reduces the brittleness of concrete [13]. The combination of constructional steel bar and steel fiber can optimize the form of components, while improving the safety of the bridge structures.

In general, the average tensile strength of UHPC (without fiber) obtained by the direct tensile strength test is 7–10 MPa. The average tensile strength value in the Japanese code is suggested to be 5 MPa [14], while the French SETRA/AFGC code proposed the direct tensile strength and flexural strength values of 8 and 8.1 MPa respectively. On the other hand, the tensile strength of UHPFRC (including fiber) is often higher, ranging from 7 to 15 MPa [15].

1.3.3. Durability

UHPC has very low water-binder ratio, high packing density and low porosity, so higher resistance to harmful medium erosion, lower permeability and better wear-resisting performance would gained in its application [16]. Pimienta and Chanvillard [17] tested UHPC elements at the environment with ammonium sulfate, calcium sulfate, acetic acid, nitrate and sea water. The test results were very encouraging, because there are no weight and strength loss for UHPC members. The following Table 3 compares the durability of several types of concrete.

It can be seen that UHPC is superior to common concrete in terms of resistance to chloride ion permeability, carbon resistance and wear-resisting performance. Therefore, it has a broad application potential under special environmental conditions (especially corrosive environment).

1.3.4. Inadequacies of mechanical properties research for UHPC

With regard to the mechanical properties and other characteristics of UHPC materials, researchers have conducted a series of studies on the dependencies of raw material properties to mix ratios and curing conditions. Although there are some variations to the specific parameters (such as compressive strength, elastic modulus, etc.) obtained through tests, the overall properties exhibited were very close in general. Especially, UHPC materials have excellent mechanical and durability properties, compared to the conventional concrete materials. However, the engineering applications of UHPC still remain in an exploration phase. Continuing studies are necessary for further improving and stabilizing the material properties.

At present, there are no uniform standards for the UHPC property test method and a quality evaluation index. In addition, some difficulties need to be overcome, which may include (1) the transformation relationship between various sizes of test specimens is still not available for the compressive strength. The relevant uniform calculation formula needs to be developed; (2) the difference between the test results of using different testing methods for tensile strength lacks reasonable interpretation through analytical model; (3) the relationship between elastic modulus and strength has not yet been identified. Other remaining issues that must be addressed systematically in the future studies mainly are: failure criteria, the relationship between microscopic structure and

Table 2
Average compressive strength under different test conditions.

Curing	Batch Description	Average Compressive Strength (MPa)
Steam	Cubes/Cylinders Compression	210
Untreated	Cubes/Cylinders Compression	149

Table 3
The comparison of the durability of ordinary concrete and UHPC.

Properties	C60	C80	UHPC
Chloride ion permeability ($\times 10^{-8}$ cm^2 s^{-1}) [18]	2.556	1.08	0.405
Carbonization depth (mm/28 d) [19]	4	1.37	0
Wear-resisting coefficient [19]	4.0	2.8	1.3

macroscopic properties, and the structural stability and durability of materials with low water-binder ratio.

2. Application of UHPC in bridge engineering

The use of UHPC materials in field of architecture predates that in bridge engineering, on which UHPC first appears in 1997. There are quite a few UHPC bridges worldwide, and UHPC is used as a major or part of building materials in bridges mainly exist in Asia (Japan, South Korea, Malaysia, China, etc.), Europe (France, Germany, Austria, etc.) and North America (USA and Canada).

2.1. UHPC application in bridge bearing component

The following Table 4 is summarized and the typical bridges in the application example are analyzed briefly.

2.1.1. Canada Sherbrooke Overpass

In 1997, the first UHPC pedestrian bridge in the world was built in Sherbrooke Quebec, Canada (Fig. 1), marking the formal application of UHPC in bridge engineering. At that time, the local government hoped to use an unprecedented new type of bridge to demonstrate the up-to-date achievement in bridge construction, and contrasted the new bridge with its adjacent old steel truss girder bridges, highlighting the elegant aesthetic effects of the prefabricated space truss of the bridge. The bridge superstructure is a posttensioned open-web space truss composed of six prefabricated match-cast segments that were assembled on site using internal and external post-tensioning. The deck and top and bottom chords are made of UHPC with a compressive strength of 200 MPa. For the diagonal web members, the UHPC is confined in stainless steel tubes and can withstand 350 MPa in compression. The 3 m deep truss spans 60 m across the Magog River (in dowtown Sherbrooke) in a circular arch [23].

Due to using the new materials and design method, this overpass structure has demonstrated many advantages, such as excellent durability and low cost for maintenance, etc. The construction of the Sherbrooke Overpass with success was a remarkable event that symbolized a new door opened for application of UHPC materials in bridge engineering.

Fig. 1. Canada Sherbrooke Overpasss. (source: Blaise, P.Y. and Couture, M. Precast, "Prestressed Pedestrian Bridge-World's First Reactive Powder Concrete Structure", 1999).

2.1.2. American Mars Hill Bridge

The United States Federal Highway Administration (FHWA) initialized the UHPC research program in 2001. FHWA has completed a number of research projects since then and continuously promoted applications of UHPC in bridge engineering in the United States. As a direct result of five years of collaborative research conducted by FHWA, the Iowa Department of Transport, Iowa State University and Lafarge North America, the Mars Hill Bridge was built in Wapello County, Iowa in 2006, which is the first UHPC bridge in the North America. As shown in Fig. 2, the bridge is a single span bridge with prefabricated section length of 33.5 m. Each

Table 4
Application examples of UHPC in bridge bearing component.

Name	Country	Year	Application location	Purpose of using UHPC
Mars Hill Bridge	United States	2006	I shaped beam [20]	Promote UHPC materials and explore material properties
Cat Point Creek Bridge	United States	2008	I shaped beam [21]	Utilize material tensile properties to simplify construction
Jakway Park Bridge	United States	2008	PI shaped beam [22]	Provide guidance for future designs employing UHPC pi-girders
Sherbrooke Overpass	Canada	1997	Prestressed, post-tensioned space truss [23]	Explore new materials and new structures Improve the durability Harmony with the environment
Glenmore Pedestrian Bridge	Canada	2007	Prestressed T-beam [24]	Resistance to weathering and easy maintenance
PS34 Bridge	France	2005	Box girder [25]	Lighten the structure and modify the bridge design and its integration in the concerned environment.
Pinel Bridge	France	2007	Prestressed T beam [26]	Utilize UHPC durability and faster construction speed
Pont du Diable Pedestrian Bridge	France	2008	U shaped beam [27]	Increase span length and pursue light graceful shape
Friedberg Bridge	Germany	2007	PI shaped beam [28]	Utilize supreme durability characteristics to replace an existing, damaged timber structure
Shepherds Gully Creek Bridge	Australia	2005	Precast, pretensioned I-beam [29]	Experimental bridges to improve the bearing capacity and replace the original ageing timber bridge
WILD Bridge	Austria	2010	Arch rib [30]	Environmental coordination and slender and light structures
GSE Bridge	Japan	2008	U shaped beam [31]	Great enhancements in concrete strength, leading to Lighter weight construction and more efficiency of materials
Papatoetoe footbridge	New Zealand	2005	PI shaped beam [32]	Reduce beam height and cost of substructure and erection
Peace Bridge	South Korea	2002	PI shaped beam [29]	Commemorate diplomatic relations with France and improve arch performance
Office Pedestrian Bridge	SouthKorea	2009	Cable-stayed bridge [33]	Light-weight structure and reasonable stress
Kampung Linsum Bridge	Malaysia	2010	U shaped beam [34]	Remove shear components and Utilize UHPC considerable flexure and shear capacity
Celakovice Pedestrian Bridge	Czech Republic	2013	segmental deck [35]	Low maintenance and reasonable life cycle cost
Luan Bai trunk Railway Bridge	China	2006	T-beam [36]	Improve the bridge's lifetime performance and durability
Fuzhou University Landscape Bridge	China	2015	Arch rib [37]	Experimental bridge to promote the use of UHPC
Yuan Jiahe Bridge	China	2017	Πshaped beam [38]	Reduce weight for convenient construction

Fig. 2. American Mars Hill Bridge. (Source: www.ductal.com).

prestressed beam contains 47 bundles of low relaxation prestressed steel strands with a diameter of 15.2 mm. Due to many innovative features of this bridge, such as a reduced amount of structural reinforcing steel, simple aspect and using longer and thinner beams, in 2006, this construction project won a PCA (Portland Cement Association) Concrete Bridge Award.

2.1.3. American Cat Point Creek Bridge

This bridge, locates in Virginia, USA has 10 spans, including one that was built using UHPC (Fig. 3), with features of thinner, lighter girders. The single beam of the bridge is 24.8 m long and 1.14 m wide without any ordinary steel bar. The bridge was constructed using the standard compressive strength of 83 MPa and 159 MPa. Because the high tensile property of UHPC was utilized, the design and construction procedure for rebar were greatly simplified.

2.1.4. American Jakway Park Bridge

In 2008, the first PI-shaped UHPC bridge-Jakway Park Bridge was built in Buchanan County, Missouri, USA on the basis of in-depth study of UHPC (Fig. 4). There are three PI-shaped beams in the bridge where the cross section is similar to the double T section, but there is a prominent part at the bottom. This is an exploration of the new form of UHPC girder bridge with a view to making more rational use of new materials. The one-by-one specimen test of the UHPC beam in this form was carried out before the practical application. The model proved that the bridge of this type had sufficient bearing capacity to accelerate the construction of the bridge and could be prefabricated with the existing prestressed facilities [39].

The construction of the Jakway Park Bridge has demonstrated the large potential for the use of UHPC in bridges, especially in

Fig. 4. American Jakway Park Bridge. (Source: www.ductal.com).

PI-beams. Through this project, the bridge design engineers accumulated more experiences in application of this type of unique material, which may help engineers to further explore the material's characteristics and reduce the cost of future projects.

2.1.5. Peace Bridge

South Korea has actively promoted the application of UHPC materials and has made remarkable progress in UHPC materials application research in bridge engineering in recent years. In 2002, the Peace arch bridge was completed and it is the world's first and the largest UHPC arch bridge (Fig. 5). The main arch span of the bridge is 120 m, with a PI-shaped cross section, which is 130 cm high and 430 cm wide, and the top plate is 3 cm thick. The transverse stiffening ribs with 10 cm height are set at 122.5 cm each distance, and longitudinal stiffening ribs are set at both ends. The main arch is composed of prestressed assembled 6 precast segments. When the main arch ring was spliced, the cast-in-place method was used both in wet joint between the cast-in-place segments and the gap between the closure segments and the arch ribs.

The completion of the Peace arch bridge may be regarded as a new milestone in the UHPC applications for improving the mechanical and construction performances as well as efficiency of arch bridges.

2.1.6. Wild Bridge

In 2010, Austria constructed the world's first UHPC highway arch bridge -Wild Bridge (Fig. 6). The rise of the arch is 18.30 m and the overall length of the bridge amounts to 157 m divided into: 9 spans of 15.0 m and 2 extreme spans of 11.0 m. Two very light

Fig. 3. American Cat Point Creek Bridge. (Source: www.ductal.com).

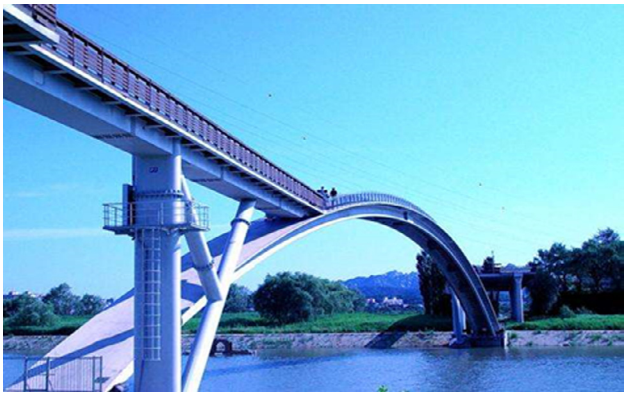


Fig. 5. South Korea Peace Bridge. (Source: www.seoul.go.kr.com).

Fig. 6. Wild Bridge. (source: Nguyen, K., et al. "Assessment of serviceability limit state of vibrations in the UHPFRC-Wild bridge through an updated FEM using vehicle-bridge interaction", 2015).

and slender polygonal arches are arranged side by side with span of 69 m. Each arch consists of precast elements (six straight beams and eight node elements) which are reinforced by steel fibers but do not contain any conventional passive steel reinforcement. Eight node elements are situated at the bends of the arch. They are called as knee nodes. The beams are up to 16 m of length and have an orthogonal cross section measuring 1.2 m [30]. The structure of UHPC truss arch structure is very graceful, which is harmonious with the scenic canyon environment.

Considering the load carrying feature of an arch bridge, the UHPC material is a good choice to provide the demanded compressive capacity for the bridge's arc structure, but produce much less permanent weight load. Consequently, the axial force and bending moments in arch ribs as well as material dosage needed can be reduced. The Wild Bridge represents a new attempt by bridge engineers both in reducing the weight of the arch bridge and in increasing slenderness ratio of the arch rib through using the UHPC materials. The success of this bridge has also shown that many other benefits from application of this type of materials to the arch bridges can be gained, such as excellent mechanical performance, longer durability and economic efficiency, etc.

2.1.7. Japan GSE Bridge

GSE Bridge constructed in Japan is a single span simply supported girder bridge (Fig. 7). The bridge is 46 m long and 16.2 m wide. The main beam adopts a separate three cell single box composed of U-shaped UHPC precast beam and C40 concrete cast-in-place bridge deck. The base plate of the u-shaped beam is 22 cm thick and the web is 15 cm thick. Each main beam is divided into seven prefabricated sections, which are connected by wet joints between the segments, and then they were assembled into the entire bridge by the internal prestressing cables.

For satisfying the requirements of low height and light weight for the bridge, the end girder height of the bridge was designed with only 1.86 m (girder height to span ratio = 1/25) and the self-weight was reduced by 40% compared to a conventional concrete bridge.

Fig. 7. Japan GSE Bridge. (source: Koichi Maekawa, "Designing & Building With UHPFRC Chapter 12", 2011).

2.1.8. Kampung Linsum Bridge

Malaysia constructed the first UHPC-RC highway composite bridge in 2010, which is located in Kampung Linsum Canyon, across the Sungai Linggi River. The elevation of the bridge is shown in Fig. 8. The span of this bridge is 50 m. The section size of the U-shaped beam is 1.75 m in height, 2.5 m in width at the top and 1.4 m in width at the bottom, and the web thickness is 15 cm. The RC bridge deck is 4 m wide and 20 cm thick, using cast-in-place construction method. The UHPC beams of the bridge are not equipped with any shear reinforcement and they are designed for a service life of 120 years. UHPC bridge engineering application in Malaysia is growing fast since the completion of Kampung Linsum Bridge.

2.1.9. Celakovice Pedestrian Bridge

In 2013, a 156 m-long pedestrian cable-stayed bridge was constructed in the Czech Republic (Fig. 9), which passes over the Labe River in Celakovice. Because bridge piers erected from the river's waterway was not allowed, the bridge owner determined to design and construct a cable-stayed bridge. The main beam of the bridge

Fig. 8. Kampung Linsum Bridge. (source: Voo, Y.L. and Foster, S.J., "Malaysia First UHPC Prestressed Motorway Bridge", 2008).

Fig. 9. Celakovice Pedestrian Bridge. (source: Koukolík P et al. "Construction of the First Footbridge Made of UHPC in the Czech Republic", 2015).

is designed as a beam-slab type, which is 3.6 m in width and 60 cm in height. The thickness of the intermediate plate is only 6 cm. The main girder of the bridge is constructed by cantilever assembly method. The length of prefabricated section is 12 m, and each main tower was built up with only 7 prefabricated beams with cantilever hoisting construction on the main span. Due to using UHPC as the construction material for the beam, the weight of the superstructure and the distributed dead load on the bridge tower are reduced markedly. This bridge became a classic engineering in elegance and light weight.

2.1.10. Luan Bai Dried-Canal Railway Bridge

Luan Bai Dried-Canal Railway Bridge built in 2006 is the first UHPC bridge in China It was a pilot project in application of UHPC to the railway bridges in China in order to meet the continuous and quick development needs for China's railway network system as well as to reduce the overall cost and improve the bridge's lifetime performance and durability. This railway bridge uses 12 UHPC T-beams with a span of 20 m. The beam height is 1.35 m and the thickness of the mid-web is 18 cm.

2.1.11. Yuan Jiahe Bridge

The bridge is the first composite girder bridge using UHPC PI-beams in China (Fig. 10). The span of the bridge is 22 m, and the width is 17.75 m, 7 pieces of UHPC prefabricated PI-beams are arranged in the cross section. The monolithic UHPC prefabricated PI-beam has a width of 2.5 m, a height of 0.93 m, a web thickness of 10 cm, and the thinnest part of the top plate is only 5 cm. The self-weight of a UHPC beam is only a half of the weight of a conventional hollow beam with the same section area. Therefore, the lifting and installation time for the UHPC prefabricated PI-beam could be significantly reduced, and the average lifting and installation for each UHPC beam only lasted 21.5 min. In addition, due to the lighter weight with the bridge superstructure, the permanent load applying on the substructure's pile foundations can be reduced, that means the used materials and the construction difficulties in constructing foundation can be also reduced. So the overall cost for the entire bridge construction would not increase significantly. This project demonstrated a great potential by using UHPC for rapid urban bridge construction for the future in China.

Fig. 10. Yuan Jiahe Bridge. (Source: http://dcem.tongji.edu.cn).

2.2. UHPC application in bridge joints

In order to realize a safe and lasting highway traffic system, it is necessary to consider all parts of the bridge, including the joints (such as transverse and vertical wet joints, expansion joints, etc.). Table 5 summarizes the UHPC application at the joints in bridge engineering.

In the bridge engineering, in order to ensure the connection performance, the conventional connection method of prefabricated components requires complicated detailed reinforcement structure, which increases the difficulty of construction and achieving the required mechanical properties in the connection area. UHPC materials provide one of solutions for connection design and construction problems for the prefabricated bridge systems with their high compressive strength, high tensile strength, low creep and excellent durability. The UHPC could make the details of the reinforcement in the connection area easier, thereby enhancing the constructability of the components and simplifying the on-site assembly process. The UHPC materials allow to use a small, simple connections while providing better overall performance.

2.3. UHPC application in bridge deck pavement

The deck pavement belongs to the direct wear portion of the bridge structure, which is not only affected by vehicle friction, but also affected by erosion of the rain and thermal expansion.

In China, the lifespan of bridge deck pavement has dropped dramatically with the continuous increase of traffic loads in recent years, so some researchers consider using UHPC materials instead of the traditional paving materials to mitigate this problem. Table 6

Table 5
Application of UHPC in bridge joints.

Name	Country	Year	Application
State Route 31 Bridge	United States	2009	Joints between deck bulb tees [40]
Fingerboard Road Bridge	United States	2011	Joints between deck bulb tees [41]
U.S. Route 6 Bridge	United States	2011	Longitudinal and transverse joints between beams [42]
State Route 42 Bridge	United States	2012	Joints between full-depth deck panels and shear pockets [43]
Pulaski Skyway	United States	2016	Joint fill connections between the slabs and the sheer pockets
Rainy Lake Bridge	Canada	2006	Joints between precast panels and shear connector panels [44]
Sunshine Creek Bridge	Canada	2007	Joint fill between adjacent box beams and between precast curbs [45]
Hawk Lake Bridge	Canada	2008	Joint fill between adjacent box beams and between precast curbs [45]
Buller Creek Bridge	Canada	2009	Joint fill between adjacent box beams and between precast curbs[45]
Eagle River Bridge	Canada	2009	Joint fill between adjacent box beams and between precast curbs and to establish live load continuity [45]
Highway 105 Bridge over Buller Creek	Canada	2009	Joint fill between adjacent box beams and between precast curbs [45]
Wabigoon River Bridge	Canada	2010	Joint fill between adjacent box beams and between precast curbs [45]
Hawkeye Creek Bridge	Canada	2012	Joint fill between adjacent box beams and between precast curbs [43]
Blackwater River Bridge	Canada	2013	Joint fill between adjacent box beams and between precast curbs
Westminster Bridge	Canada	2014	Longitudinal joints to connect superstructure modules.
Nipigon River Bridge	Canada	2016	Connections of precast tower segments to cast-in-place tower segments and the connections of longitudinal and transverse joints to steel girders and beams

Table 6
Application of UHPC in bridge deck pavement in China.

Name	Year	Position	Bridge type
Ma Fang Bridge	2011	Guangdong Province	Simple Box Girder
Buddha Chen Bridge	2014	Guangdong Province	Variable section continuous steel box girder [46]
Hai He Bridge	2015	Tianjin	Hybrid beam cable-stayed bridge [48]
Tong Hui Bridge	2015	Beijing	Deck beam arch combination bridge [48]
Dong Ting Lake Second Bridge	2015	Hunan Province	Plate-truss Composite suspension bridge [48]
Rong Jiang Bridge	2016	Guangdong Province	Hybrid beam cable-stayed bridge

shows examples of bridge deck pavement using UHPC materials in China in recent years.

2.3.1. Rong Jiang Bridge

Rong Jiang Bridge (Fig. 11) is a 60 m + 70 m + 380 m + 70 m + 60 m composite beam cable-stayed bridge with double towers and double cable planes, where the middle span is the 520 m steel box girder, and the side span is 60 m + 60 m prestressed concrete box girder.

The pavement layer was made of SMA asphalt concrete (SMA-13), and the lower layer adopted epoxy asphalt concrete (EA-10) at first (Fig. 12(a)), but the effect was not impressive. Then, a thin layer of UHPC layer was laid on the steel main beam, and the steel box girder was transformed into STC composite continuous beam structure, as shown in the Fig. 12(b). This setup greatly improves the toughness and durability of the deck pavement.

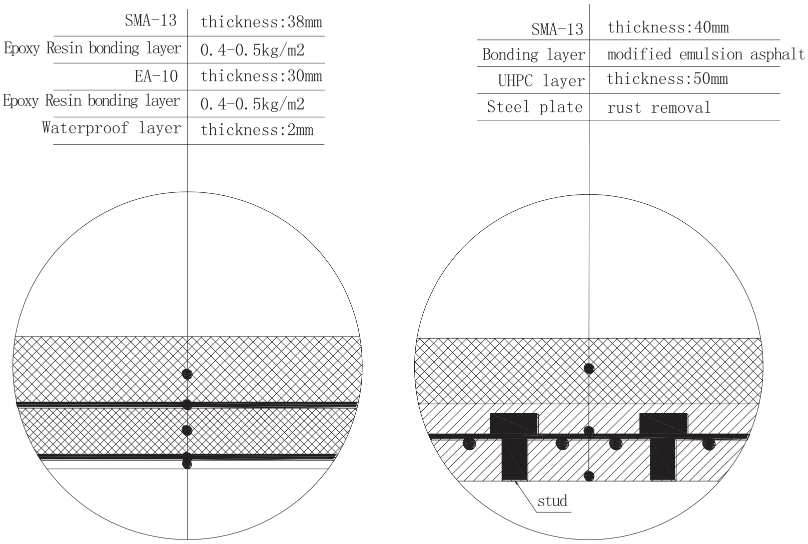
Fig.11. Rong Jiang Bridge.

2.3.2. Ma Fang Bridge

Ma Fang Bridge, which was constructed in 1984, is a Highway-Railway Dual-Purpose Bridge located in Zhao Qing City, Guangdong Province, China. Since it was constructed, many bridge renovations have been made, in which several types of deck pavement material were used, but the results were still not satisfied by the bridge owner. In order to address this problem, researchers and engineers carried out full-scale UHPC pavement model test of the bridge. On the basis of the affirmative results from pilot tests, the UHPC was applied to the 11th span deck pavement of the Ma Fang Bridge. Since then, the China railway research institute has conducted two tests on the structure of the 11th span-light composite beam of the bridge [47]. Test results showed that there was no crack in the bridge surface after the use of UHPC, the stiffness and the local stress of the bridge were greatly improved.

2.3.3. Humen Bridge

The orthotropic steel bridge panel has the advantages of high bearing capacity and good integrity, so it has been widely used in large span steel bridges. However, the defect of paving layer becomes the important factor that restricts its development. Based on the bridge deck reconstruction project of Humen Bridge, Ding et al [48] designed a full-scale model and carried out the static load test and the fatigue load test. The test results showed that there were no visible cracks appeared in the UHPC pavement and the measured stress data and other damage indicators also did not



(a) (b)

Fig.12. Deck pavement detail construction of Rong Jiang bridge.

exceeded the material strength capacity. The great performance of the UHPC used for bridge deck pavement was exhibited evidently through this testing.

2.4. Application prospect of UHPC in long-span bridge

At present, some types of flaw appeared in long-span Bridge, including:(1) The general deflection and crack of prestressed concrete continuous box girder; (2) Steel bridge deck pavement and bridge surface structure crack; (3) Concrete crack in the negative moment area of steel -concrete composite beams [49].

The effect of the deflected and cracked concrete beam of long-span Bridge has been a serious issue. Now, scholars have proposed the one-way prestressed UHPC thin-wall continuous box girder structure to solve these problems, and carried out conceptual design on the continuous box girder bridge of UHPC. The study shows that this new type of UHPC structure can effectively reduce the crack and deflection of the girder bridge [50]. The use of UHPC with strong tensile strength instead of the conventional concrete as the bridge system can greatly improve the stiffness of the bridge deck, significantly improve the stress of the pavement layer, reduce the fatigue stress of the steel structure and effectively reduce the crack [51].

The development of the design and construction technology for long-span bridges have been advanced more and more rapidly in recent decades. Innovations made in structural design and construction are often related to the application of new materials. UHPC has a great potential in this aspect.

2.5. Thoughts on the popularization of UHPC in bridge engineering

2.5.1. The key constraints for the application of UHPC in bridge engineering

Although UHPC has been applied in the 42 bridges described in the article, there are some restrains that may limit its extensive applications.

(1) Cost of raw materials: The cost of raw UHPC materials is the most concerned factor by the bridge owners and designers, and much of the raw materials (such as silicon, steel fiber) is expensive than normal concrete. Certainly, the bridge owners and design engineers should also realize the use of UHPC materials not only reduces the amount of material used in the structure itself, but also brings indirect economic benefits from heavy reduction of construction and foundation requirements, comprehensive economic benefits of improved durability, and social benefits for environmental protection and energy conservation, these factors need to be considered comprehensively.

In addition, UHPC is very strict in the requirement of using raw materials, the diameter of the gravel, the kinds of fiber and water reducer will have an impact on the performance of the finished product. Therefore, how to prepare the UHPC with stable performance under different conditions has become the primary factor restricting its wide adoption.

(2) Maintenance requirement: the UHPC needs high temperature maintenance during construction in order to obtain high material strength. However, the bridge construction site may not be provided often with the corresponding equipment used for such maintenance. Therefore, the UHPC is mostly applied in a prefabricated manner, but this will limit the choice of construction methods and bridge structures.

High-performance concrete is embodied in the entire process of quality control system for the production and use of concrete, not just raw materials. It is a systematic project and requires the cooperation of various departments such as raw material production, concrete preparation, concrete construction and structural design to achieve the desired results. At present UHPC material laboratory preparation method has no problem, the researchers are committed to the complex laboratory preparation technology into a low-cost engineering and practical preparation technology, but the practical preparation technology is not mature enough. This will affect UHPC competition with ordinary concrete and high-strength concrete.

(3) Specifications: At present, corresponding uniform guidelines and standards for numerical modeling, testing, design and construction should be established as ordinary concrete. In addition, before the large-scale application of UHPC materials, it is necessary to develop methods for checking damage, effective maintenance and repairing or replacing UHPC components, and these need to be standardized to promote the UHPC application.

(4) Deficiencies of UHPC: UHPC materials have a lower water-binder ratio and incorporate a large amount of active admixture, as the hydration of the cementitious material progresses, its shrinkage also increases. If handled improperly, it may cause cracks. In addition, the corrosion of the surface steel fiber is a question worthy of attention. Specifically, the protective layer of steel fiber near the concrete surface is small and may expose the surface, so the surface steel fibers are at risk of rusting in a wet or corrosive environment (chlorine, acid, etc.). The incorporation of steel fibers plays an important role in improving the fatigue and tensile properties of UHPC. However, fiber content, shape, size, fiber orientation etc. will affect the overall properties of the material, which need to be carefully considered. At present, there are still many problems to be solved and continuing studies are necessary for further improving and stabilizing the material properties.

2.5.2. The main research direction in the future

Based on the current research status, the authors think the research direction of UHPC in the future mainly includes:

(1) Fundamental modeling for static and dynamic behaviors of bridge elements/components and connections fabricated using UHPC materials. The models can be involved in popular commercially-available software (e.g., SAP2000 and ANSYS, etc.).
(2) Development of guidelines and standards for design, construction, testing and long-term performance monitoring and evaluation (including seismic, wind-resistant, vessel collision, vehicle collision performances).
(3) Design and construction method of prestressed UHPC girders developed for long-span bridges.
(4) Optimal performance and reliability based design methods involving in bridge's entire life-time cost considering design, construction, maintenance, and retrofit for the damaged components that may be caused by some extreme events, such as earthquake, hurricane, vessel collision etc.

3. UHPC studies in other aspects

3.1. Seismic resistance

The seismic performance of the bridge structure may be improved by using UHPC due to its superior mechanical properties,

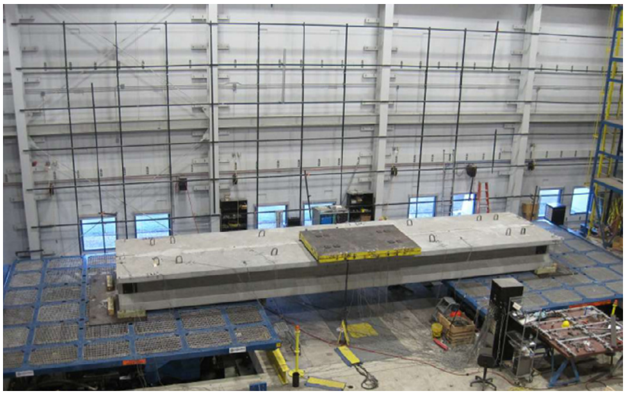


Fig.13. Set-up of Shake Table Test.

Fig.14. UHPC Connection of Two Girders.

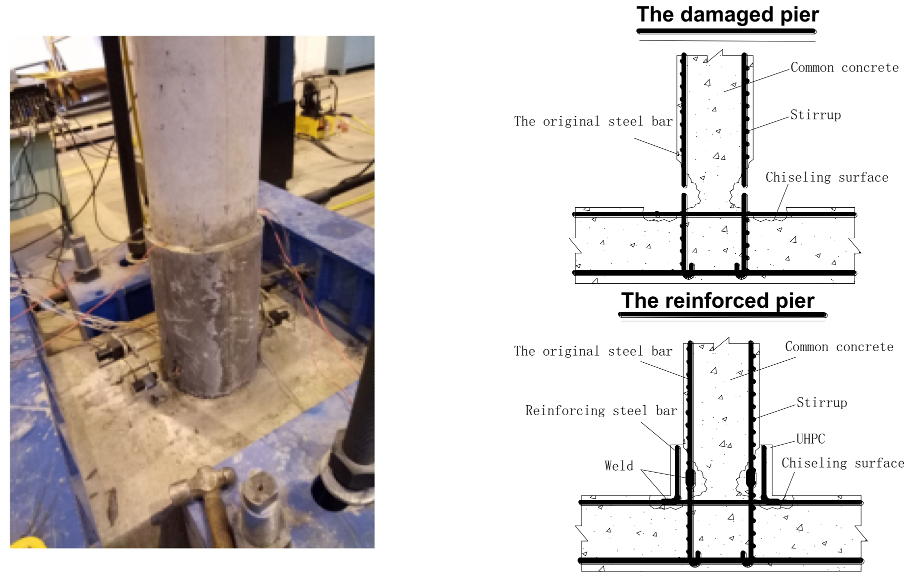
and using UHPC materials to strengthen the seismic resistance of bridge structures will have great potential

The seismic performance of UHPC has been studied by many researchers since it was used in the bridge engineering. At MCEER (Multidisciplinary Center for Earthquake Engineering Research, USA), researchers [52] carried out experimental study to evaluate the seismic performance of two precast deck-bulb-tee girders with field-cast UHPC connections (shown in Figs. 13 and 14), and a series of shake table tests were performed. Based on the experimental results, it can be concluded that the UHPC connections with short, straight rebar provide sufficient seismic resistance under high-level of seismic loadings.

Ju et al. [53] carried out pseudo-static test for 18 UHPC concrete columns and studied the influence of multi-factors on the damage pattern, hysteresis characteristic, skeleton curve, stiffness bearing capacity and ductility of the concrete column of UHPC. It was found that the stirrup ratio, axial compression ratio and steel fiber content had influence on the ductility and energy dissipation capacity of UHPC. Peng et al. [54] performed slow cyclic loading tests for six groups of reinforced concrete columns connected with UHPC materials. The results showed that the bearing capacity of UHPC post-coating columns was increased by 3.1% to 31.9% compared with that of the entire column, and the ductility coefficients were generally similar.

The authors of this article studied the effect of using UHPC materials to repair the plastic hinged region of the pier after earthquake damage by designing a set of reinforced concrete pier specimens to carry out pseudo-static tests of low-cycle reciprocating loads. The experiment set-up and the specimens are shown in Fig. 15(a).

The pseudo-static test of the bridge pier was carried out to form a plastic hinge region near the bottom of the pier, and then the UHPC was used for reinforcing and strengthening (Fig. 15(b)). The conclusion was provided through the comparison of the pseudo-static test data of the bridge pier and the reinforced pier under the same conditions. Fig. 16 illustrates two examples of



(a) Test set-up and column specimen

(b) Schematic of the damaged and reinforced columns

Fig.15. The experimental device and the specimen.

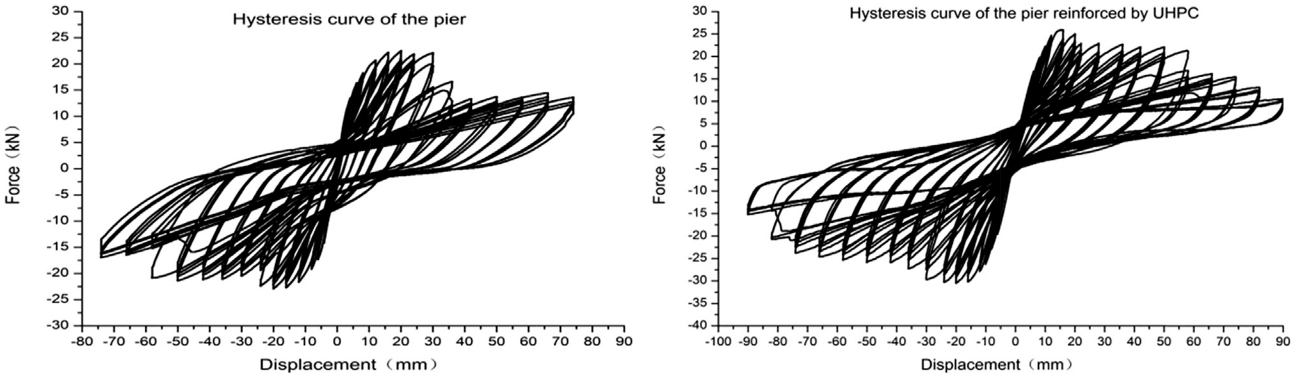


Fig. 16. The comparison of the hysteresis curves of the bridge pier and the reinforced pier.

the hysteresis curves measured from specimen test. These two curves show that the ductility and bending resistance of the piers are improved to some extent.

Luo Xiao et al. [55] studied the shear behavior and shear failure characteristics, bearing capacity, ductility and energy dissipation capacity of the shear wall by studying the low cyclic reversed loading test of the three variable aspect ratio UHPC shear walls. The key factors of seismic performance of the UHPC shear wall were obtained through the simulation and experiment of finite element software. The result shows seismic performance of UHPC is much better than that of general concrete.

3.2. Anti-explosion and impact resistance performance

The characteristics of UHPC also include a significant advantage in anti-explosion and impact resistance. The studies have shown that compared with ordinary reinforced concrete columns, the plastic damage of the UHPC column and the horizontal displacement of the column are much smaller. So the UHPC columns have better explosion-proof performance [56].

Lai et al. [57] tested the penetration depth and explosion damage of different UHPC targets. Their results show that the enhanced high-performance concrete enhanced by fibers has better anti-explosion performance. Tian et al. [58] established a numerical analysis model by using nonlinear finite-element explicit dynamic analysis software. Their analysis shows that the anti-bending ability and the shear strength of the column are important means to improve the anti-detonation capability. Sheng et al [59] reviewed the experiment, theory and numerical simulation of UHPC impact performance and analyzed the influence of material composition, test method, loading method and strain rate on the impact performance of UHPC.

In addition, as a new material with high strength and high durability, UHPC can be used to replace the steel structure member in harsh environment, improve the durability of the component, and reduce the cost [16]. High strength of UHPC can also be used in the field of defense engineering.

4. Summary

UHPC materials have excellent mechanical properties and durability, which can improve the connection integrity of bridge component joints, reduce the deformation and crack problems of bridge pavement, and improve the load-carrying capacity of bridges. However, they are currently only used in small and medium-sized bridges or pedestrian bridges. It is expectable that UHPC will be used to address many issues, such as general deflection and crack of conventional prestressed concrete continuous box girder, damage of steel deck pavement and fatigue crack of steel structures, concrete crack in the negative moment area of steel-concrete composite beams and a series of challenging problems associated with long-span bridges. Although the relatively high cost of UHPC materials, maintenance requirements and the lack of standard specifications for design at current stage, more and more researchers, bridge owners and engineers have recognized its application potentials in bridge engineering. The extensive researches on UHPC's preparation techniques, material properties, structural design methods and specifications will promote wider applications and reducing the material cost.

Conflict of interest

None.

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