

APPLICATION OF ULTRA HIGH PERFORMANCE CONCRETE TO CABLE STAYED BRIDGES

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Abstract

This paper reports a systematic research (Super Bridge 200) of Korea Institute of Construction Technology (KICT) to develop a competitive cable stayed bridge system using the advantages of Ultra High Performance Concrete (UHPC). Since 2007, various structural analyses and experiments on UHPC specimens and structures have been performed to develop design guidelines and manufacturing specifications. Based on this research, KICT developed a new kind of edge girder type cable stayed bridge system using UHPC for the main span of 200 m ~ 800 m and its economic feasibility was verified. To realize the developed system, KICT designed and constructed an UHPC pedestrian cable stayed bridge with the span length of 14 m in 2009. In addition, in 2011, KICT together with a construction company designed the first UHPC highway cable stayed bridge in detail for the open tender for Jobal Bridge, and constructed an UHPC highway bridge at Andong, Korea in 2012.,

Résumé

Le présent article décrit les travaux réalisés au « Korea Institut of Construction Technology » (KICT) dans le cadre d'un programme de recherche (Super Bridge 200) dont l'objectif est de développer un concept compétitif de pont à haubans, utilisant pleinement les performances des BFUP. Depuis 2007, les travaux entrepris portaient sur le développement de méthodes d'analyse du comportement et de calcul des structures en BFUP en s'appuyant sur les résultats d'un vaste programme expérimental incluant des essais sur des structures à grande échelle. Ces travaux ont servi à la mise au point de guides de conception et de réalisation des ouvrages en BFUP. Sur la base de ces travaux, le KICT a développé une nouvelle conception de pont haubans avec un tablier constitué de poutres latérales en BFUP, et ceci pour une gamme de portée principale variant de 200 à 800 m. Une étude comparative avec des solutions classiques a permis de vérifier l'intérêt économique de cette conception. Pour valider le concept, une passerelle haubanée de 14 m de portée, a été conçue par le KICT et réalisée en 2009. En 2011, dans le cadre de l'appel d'offre pour la construction du pont autoroutier de Jobal, le KICT en collaboration avec une entreprise de construction a établi le projet détaillé d'un pont à haubans basé sur le concept développé avec un tablier en BFUP.

1. INTRODUCTION

Up to date, a number of bridges have been erected using UHPC. The Sherbrooke pedestrian bridge constructed in 1997 in Canada was the first application of UHPC for bridges. In Korea, Seonyu pedestrian bridge was built in 2002. UHPC highway bridges were also built. USA built several highway bridges such as Wapello County Mars Hill Bridge (2006), Cat Point Creek Bridge (2008) and Jakway Park Bridge (2008). Japan also applied UHPC to the highway bridges, Tokyo Int. Airport GSE Bridge (2010) and Kayokawa Bridge (2010). Many other UHPC bridges can be found from the reference [1].

Although UHPC pedestrian and highway bridges were built, it is difficult to say they are competitive in the bridge market. From the economic point of view, the UHPC bridges for a short or mid span are probably not competitive to conventional concrete bridges and steel composite bridges because of high initial construction cost.

However, it can be easily conceivable that the advantage of UHPC can be effective when it is applied to long span bridges such as cable stayed bridges. Application of UHPC to a concrete cable stayed bridge might lead to the reduction of self-weight by replacing heavy concrete sections with compact UHPC ones, which, in turn, results in the reduction of expansive cables and the size of foundation. The expensive steel sections of steel or composite cable stayed bridges might be replaced with reasonable UHPC ones without increasing the weight excessively, which, again, results in the reduction of material cost large enough to compensate the increase of the cost from the cables and the foundation.

It is not straightforward to realize this idea. Simple substitution of UHPC for concrete and steel is not enough to use maximum out of UHPC and to secure economic feasibility considering the cost of UHPC. A new cable stayed bridge system combined with UHPC most effectively should be developed. The realization of an UHPC cable stayed bridge, therefore, should be preceded by the systematic and intensive investigation of material, structure, construction and economic feasibility.

KICT launched a 6-year research project called Super Bridge 200 from 2007. This project deals with the application of UHPC to a cable stayed bridge. The total budget is approximately 17 million USD. The main goal is reducing construction and maintenance cost of cable stayed bridges by 20% respectively and extend the service life of main structural elements up to 200 years by combining UHPC and cable stayed bridge technology together. Super Bridge 200 has developed the technology for (1) improvement of UHPC behavior, (2) the design of UHPC structures such as girders and plates, (3) a light and durable UHPC deck, (4) an economic UHPC cable stayed bridge system with the main span of 200 m ~ 800 m.

2. IMPROVEMENT OF UHPC BEHAVIOR

The basic UHPC composition developed by KICT is shown in Table 1. Steel fibers are 13 mm in length and 0.2 mm in diameter, and their tensile strength is 2500 MPa. All UHPC specimens are steam cured for 72 hours at 90 degree after 24-hour curing at room temperature. The mechanical properties of the material are summarized in Table 2.

Table 1: UHPC composition (all by weight but steel fiber)

W/B	Cement	Silica fume	Sand	Filling power	Super plasticizer	Steel fiber (V_f)
0.2	1	0.25	1.1	0.3	0.016	2%

Table 2: Mechanical properties of UHPC

Design compressive strength	Design tensile strength	Elastic modulus	Poisson's ratio	Total shrinkage	Creep coefficient
180 MPa	9.5 MPa	45 GPa	0.2	600×10^{-6}	0.45

As a result of this research, the first draft of the UHPC fabrication specification was proposed in 2007 and has been updated yearly to include new research results.

Apart from developing design technology for an UHPC cable stayed bridge using the basic UHPC developed by KICT, the research to improve the performance and economic efficiency of UHPC itself was done in parallel.

This research is focused on both minimizing the amounts of fiber and maximizing the performance of UHPC. The performance of UHPC was investigated according to the aspect ratio, shape and volume content of steel fibers. To improve the flexural and tensile characteristics of UHPC, it was found that one of the promising methods is to blend two different steel fibers together. Blending macro fibers different in length can increase the tensile strength of UHPC while minimizing the reduction in constructability due to long fibres.

The result of 4-point loading tests of standard prisms (100 mm x 100 mm x 400 mm) shows, compared to the basic UHPC with 2 % of steel fiber, the flexural strength increased by 27 % (maximum 50 %) in average for the hybrid UHPC with the use of fibers of 19.5 mm and 16.3 mm in length 1 % each (Fig. 1) [2]. The diameter of the fibers is 0.2 mm for both. Accordingly, the fabrication cost of the hybrid UHPC can be reduced by approximately 70 % compared to that of the basic UHPC. Direct tensile test of the hybrid UHPC reveals the tensile strength of 17 MPa, which is estimated as one of top levels of the world (Fig. 2).

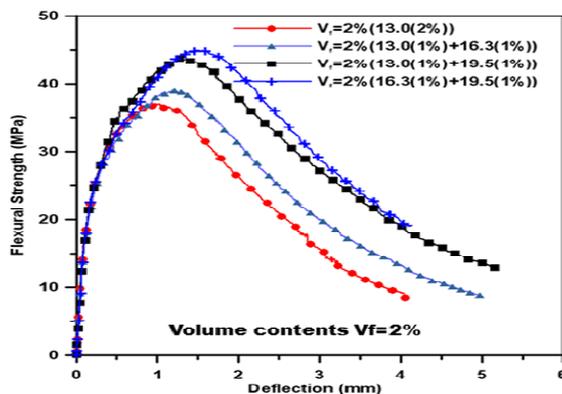


Figure 1: Flexural behavior of UHPC ($v_f = 2\%$)

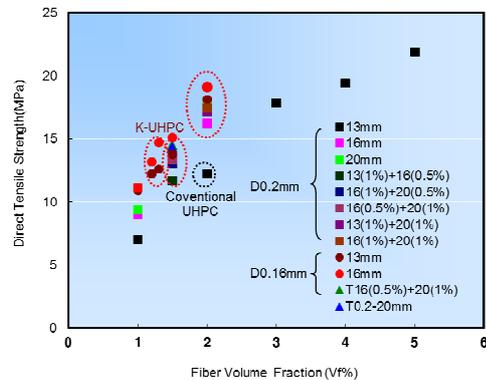


Figure 2: Tensile strength of UHPC

3. DESIGN OF UHPC STRUCTURES SUCH AS GIRDERS AND PLATES

For the structural design of UHPC, various structural tests were performed at the KICT; flexural, shear and torsional tests of UHPC girders, punching tests of UHPC plates and miscellaneous tests of reinforced UHPC structural details [3-5]. As a result of the research, the first draft of UHPC structural design guidelines was proposed in 2008 and has been updated yearly to include new findings.

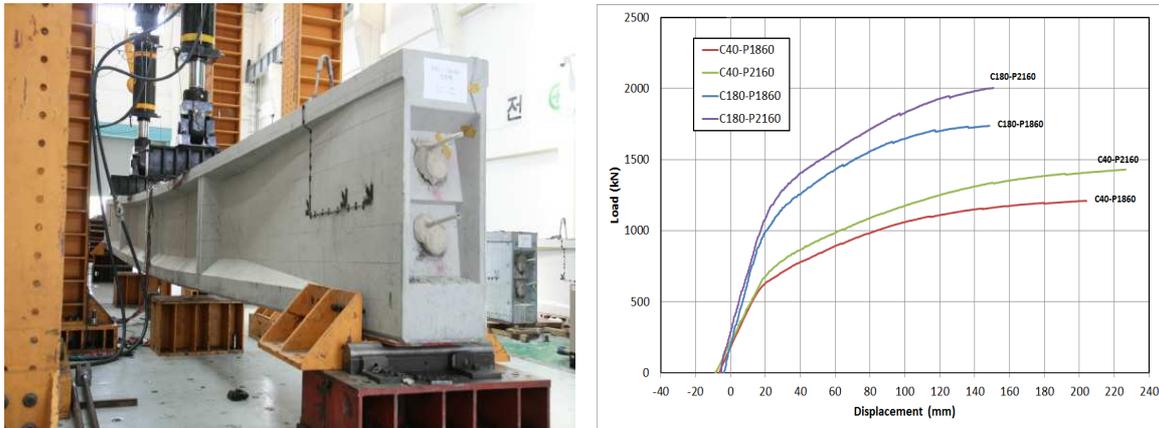


Figure 3: Flexural test and results of UHPC girders prestressed with tendons [5]

In 2008 ~2012, reinforced UHPC girders were tested to estimate the flexural strength and to find how to estimate it for the design (Fig. 3). The tested UHPC girder specimens were reinforced with rebars or prestressing tendons. It was done because, in spite of relatively high tensile strength of UHPC compared to conventional concrete, the large difference between compressive and tensile strengths of UHPC makes it necessary to use reinforcement in the UHPC flexural member such as a girder.

After first cracking, according to the increase of loading, new micro-cracks started to develop between the existing cracks and most of the cracks continued to propagate toward the upper chord without visual widening of the crack width. At ultimate load, one of the cracks started to open while other cracks exhibited practically unchanged shape until failure.

Test results show the flexural strength can be estimated reasonably well by applying stress-strain relationship with Bernoulli's assumption. The results also show that the tensile behavior of UHPC together with the effect of fiber orientation should be considered in the estimation.

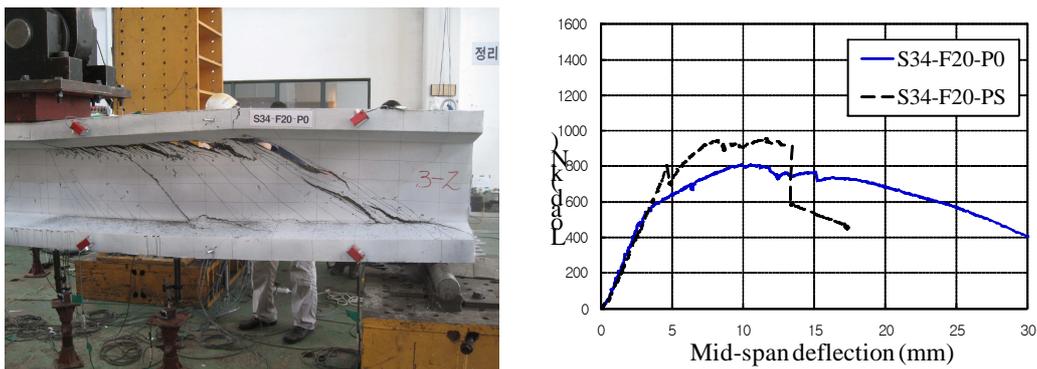


Figure 4: Shear test and results of UHPC girders without stirrups [6]

In 2010, UHPC girders without shear stirrups were tested in shear (Fig. 4). Test results showed that, as the load was increased, initial diagonal cracks occurred in the web with the degradation of stiffness (Fig. 4). However, sudden loss of the strength was not observed and the load was gradually increased with the propagation of the initial cracks to upper and lower flanges. Additional diagonal cracks in the web were occurred as well. At the failure, with

gradual decrease of the load, one of the diagonal cracks in the web was developed to the major diagonal crack (Fig. 4).

Test results also show that, with an additional term to consider the contribution of fibers after the initial cracks in the web, the shear strength formula for an ordinary concrete girder can be used to estimate reasonably the shear strength of UHPC girders without stirrups [7].

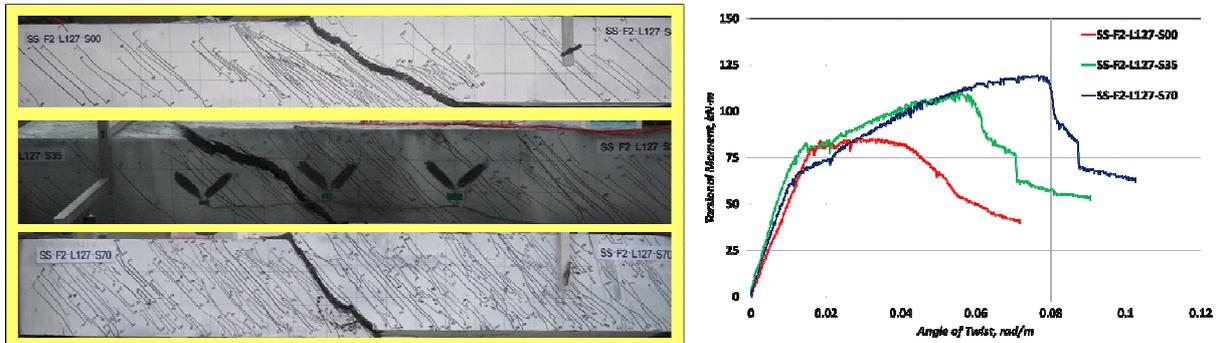


Figure 5: Torsional test and results of UHPC girders [8]

UHPC rectangular members were tested in torsion (Fig. 5). It was done because the thin-walled tube theory that is currently adapted in the code has no term to consider the tensile behavior of UHPC that is different from ordinary concrete.

The test results show that the UHPC specimens with no reinforcement did not lose its torsional strength after cracking due to the ductility of UHPC, and the UHPC specimen with longitudinal rebars only also showed a ductile behavior [8]. Those are different from the behavior of ordinary reinforced concrete members. The UHPC specimens with longitudinal rebars and stirrups showed hardening after cracking.

Based on the test results, the thin-walled tube theory was modified to consider the tensile behavior of UHPC in the estimation of torsional strength of UHPC girders [9].

KICT also did punching test of UHPC thin plates (Fig. 6) for a punching formula and miscellaneous tests to optimize structural details such as shear keys, the minimum cover thickness, bond-slip relation, crack width and spacing, development length and etc. (Fig. 7).

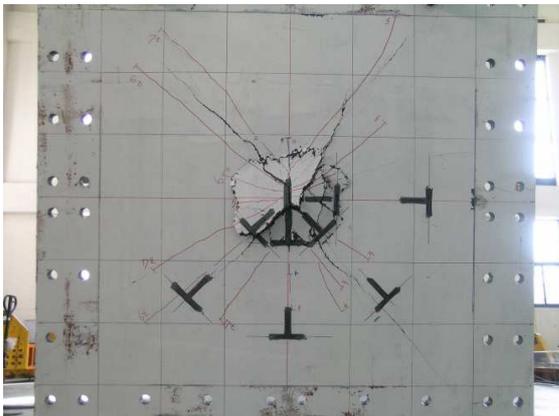


Figure 6: Punching test of UHPC plates [10]

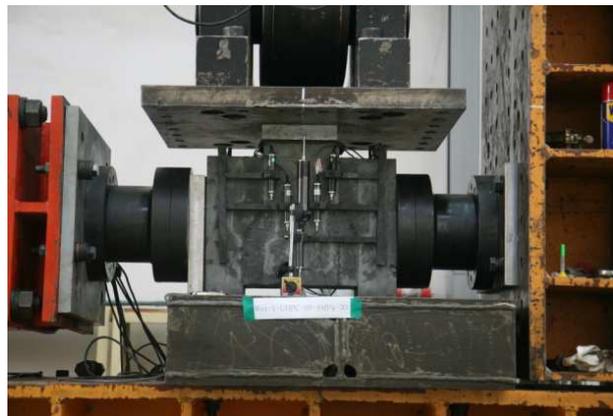


Figure 7: Shear key test of UHPC joints [11]

4. LIGHT AND DURABLE UHPC DECK

In the cable stayed bridge, the deck contributes to the weight of the superstructure largely but does relatively small to the overall construction cost. The gross economic efficiency of the bridge, therefore, could be significantly improved by reducing the weight of the deck by the adoption of relatively expensive high-performance materials.

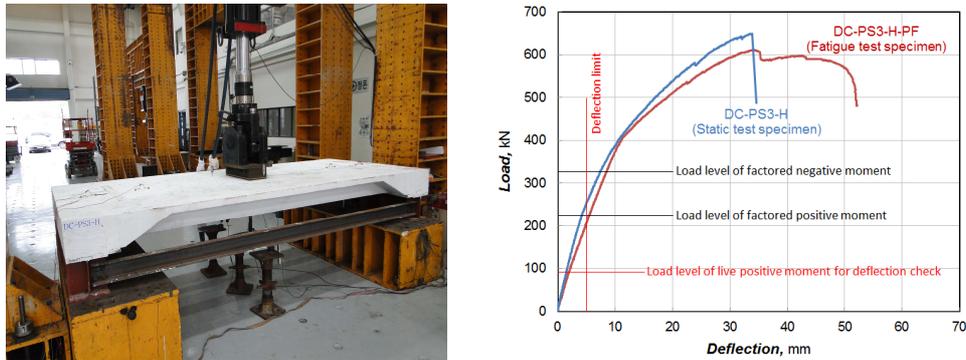


Figure 8: Test and results of UHPC ribbed decks [12]

KICT applied this idea to the deck of an UHPC cable stayed bridge. KICT has developed the UHPC ribbed deck slab (Fig. 8) with prestressing tendons as a solution to lighten the self-weight of the superstructure for a cable stayed bridge. It is composed of thin plate with 60 mm in thickness and stiffening ribs with spacing 600 mm. Its weight is about half of the conventional precast concrete deck. Optimum design and various tests were carried on to verify its behavioral characteristics and to evaluate its structural performance. Test results verified that the proposed decks satisfy the relevant design codes (Fig. 8).

5. UHPC CABLE STAYED SYSTEM

In the cable stayed bridge, the tension in the cables produces the compression in the deck and the tower. The high compressive and tensile strengths of UHPC allow for the redesign and optimization of stiffening girder and deck elements in the cable stayed bridge.

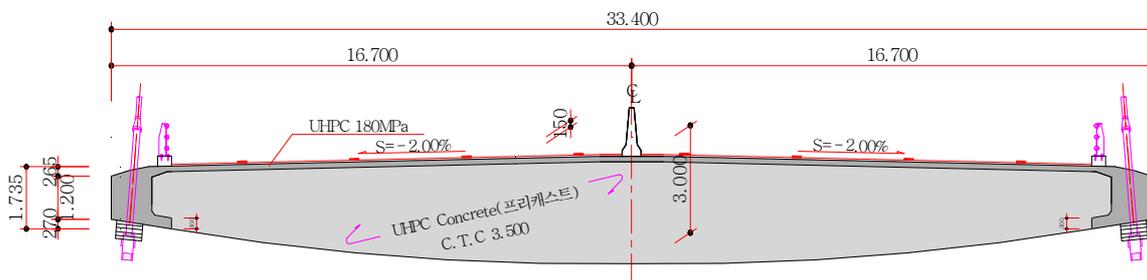


Figure 9: Cross section of an UHPC edge girder for the main span of 800 m (unit: mm) [13]

The edge girder with parabolic cross beams (Fig. 9) was developed for the low-cost UHPC cable stayed system. This system was chosen because, first of all, considering the constructability related properties of UHPC, the edge girder system is relatively easy to

fabricate compared to a typical box girder system. In addition, due to the high compressive and tensile strength, the cross section and the weight of the edge girder and the thickness of deck slab can be minimized.

The typical aerodynamic difficulties of the edge girder system can be controlled by modifying the shape of the edge girder and the cross beam. The wind tunnel test partially verified the aerodynamic performance (Fig. 10). The fabrication and connecting of 2 segments of 16.7 m wide one-half model of the edge girder system showed the constructability of the system. The moving wheel fatigue test on the fabricated edge girder system was also done to estimate the fatigue strength (Fig. 10).



Figure 10: Wind tunnel and moving wheel fatigue tests of an UHPC edge girder [13]

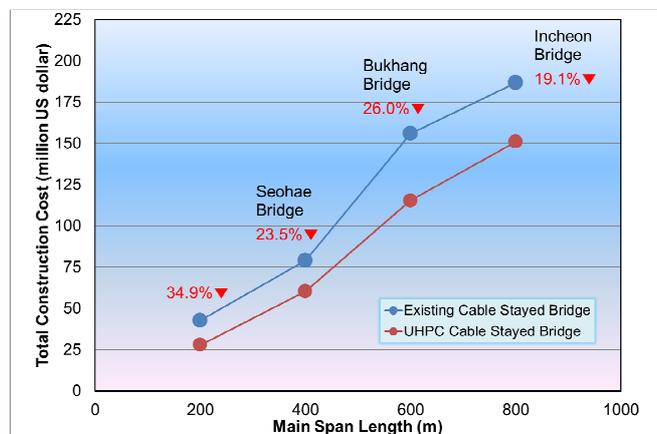


Figure 11: Cost analysis of cable stayed bridges

Cost analyses based on detailed designs show that the overall cost of an UHPC cable stayed bridge is lower over the main spans between 200 m ~ 800 m than that of a conventional cable stayed bridge (Fig. 11). Especially, the UHPC cable stayed bridge (Super Bridge 800) with the main span length of 800 m was designed in detail and compared to recently completed Incheon Bridge, the world's 5th longest cable stayed bridge with steel deck. The cost analysis showed the UHPC cable stayed bridge can save 19.1 % of overall cost of Incheon Bridge (Fig. 11).

For the main span of 200 m~ 400 m, where a concrete or composite cable stayed bridge is a dominant system, the UHPC cable stayed bridge can reduce the cost by reducing the weight of deck and, accordingly, the costs of cables and foundations. For longer span, where the

cable stayed bridge with steel deck is a dominant system, UHPC cable stayed bridges reduces the cost by replacing expensive steel deck with UHPC deck. Although the weight of the deck itself is increased and the related cost is increased more or less, the overall cost is reduced more than that due to the decrease of used steel (Fig. 11).

6. APPLICATION OF UHPC CABLE STAYED BRIDGE

In 2009, Super Bridge 200 team designed and constructed an UHPC pedestrian cable stayed bridge (Fig. 12), which connects two office buildings at KICT. As shown in Fig. 12, two precast girders per each span are connected using steel bar after bonding with epoxy (Fig. 12). The portion around the pylon was designed to be cast-in-place concrete considering the connection with the pylon.

In 2011, Daelim cooperation, one of the major construction companies in Korea, chose the UHPC cable stayed bridge for the bidding of Jobal Bridge that is planned to connect Jobal and Dunbyung islands near south coast line of Korea. Fig. 13 shows the bird's eye view of Jobal Bridge designed by the technologies developed from Super Bridge 200. The proposed Jobal Bridge is a three-tower UHPC cable stayed bridge (Fig. 13 and 14). The main span length is 200 m and the height of pylon is 90 m. The edge girder type superstructure (Fig. 14) was designed using UHPC. This is the first cable stayed bridge designed using UHPC for a highway bridge.

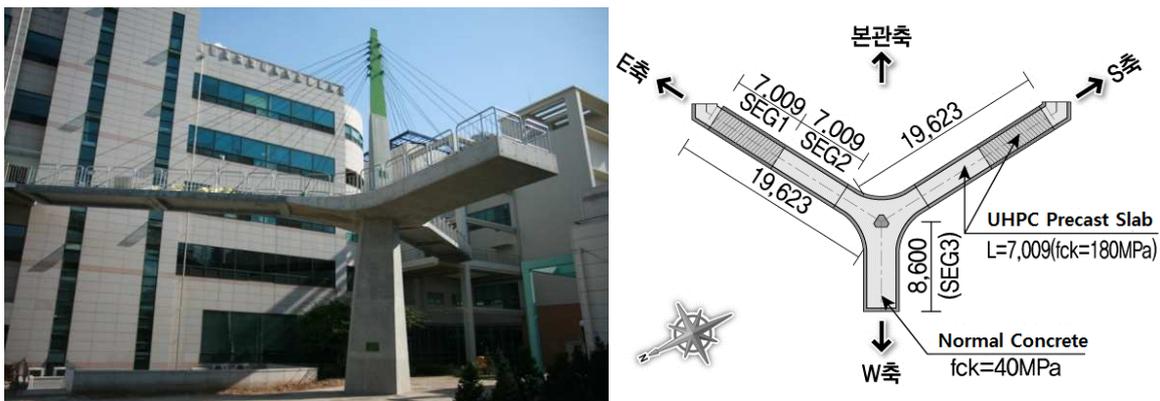


Figure 12: UHPC pedestrian cable stayed bridge built at KICT [13]



Figure 13: Bird's eye view of Jobal Bridge [13]

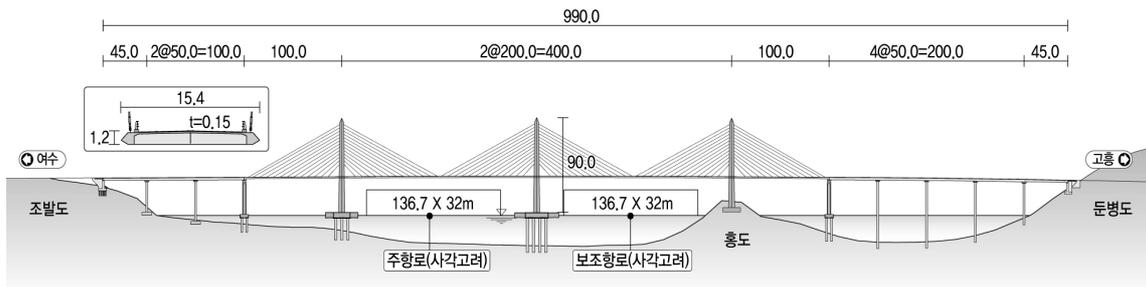


Figure 14: Jobal Bridge Plan [13]

In July 2012, the first UHPC highway bridge in Korea was built near Andong, Gyeongsangbuk-do where is famous for Hahoe Folk Village. The length and width of the bridge are 11 m and 5 m, respectively. The pi shape was selected for the cross section of an UHPC girder to use the maximum capacity of UHPC, and the super structure was composed of three girders as shown in Fig. 15. No conventional reinforcement was used.

The height of the girder is 600 mm and the thickness of the deck slab is 100 mm. The weight of a girder is only 112 kN. Cast-in place UHPC was used to fabricate the connections between girders and no reinforcement was necessary either. Portable UHPC mixer of 0.5 m³ developed by KICT was used for the mixing of cast-in place UHPC. Fig. 15 shows the UHPC highway bridge under loading test after completion. The measured deflection and the stress at the mid-span were compared to the design values. The result shows reasonable agreement between a test and an analysis.

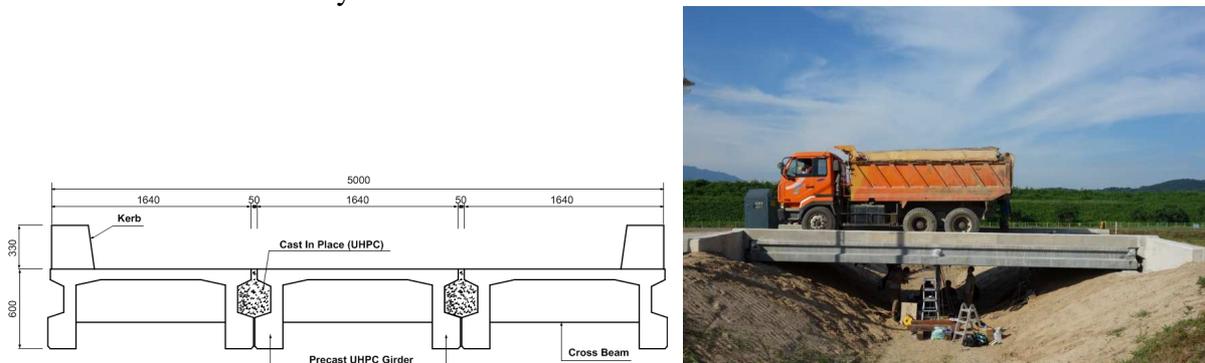


Figure 15: Cross Section and test of 1st UHPC Highway Bridge in Korea (2012) [12]

Although these bridges are not gigantic one or actually constructed, major technologies to be used in the construction of an UHPC highway bridge were successfully applied, which shows material, design and construction technology of Super Bridge 200 is ready for the market.

7. CONCLUSION

This paper presented KICT's intensive and systematic development of technology for a UHPC cable stayed bridge since 2007. KICT launched a 6-year research project called Super Bridge 200 from 2007. The purpose was reducing construction and maintenance cost of cable stayed bridges by 20 % respectively and extending the service life of main structural elements up to 200 years through combining UHPC and cable stayed bridge technology together.

As a result, Super Bridge 200 has developed technologies for (1) hybrid UHPC with tensile strength of 17 MPa, (2) design of slender and durable UHPC structures such as girders and plates based on the lots of structural tests and analyses, (3) light and durable UHPC deck based on the optimization and tests, (4) the UHPC cable stayed bridge system with the main span of 200 m ~ 800 m based on the structural optimization and detailed cost analysis. The UHPC fabrication specification and UHPC structural design guidelines were developed. And Super Bridge 200 technology was successfully applied to the design and construction of an UHPC pedestrian cable stayed bridge in 2009 and an UHPC highway bridge in 2012, and the design of Jobal Bridge in 2011, the first detailed design of the UHPC cable stayed highway bridge.

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