KICT's Application of UHPC to the First UHPC Cable Stayed Roadway Bridge

Author(s) & Affiliation: Byung-Suk Kim, Changbin Joh, Sung Yong Park, Gyung-Taek Koh, Kihyon Kwon, Jongbum Park, KICT (Korea Institute of Civil Engineering and Building Technology)

Abstract: This paper presents systematic research of Korea Institute of Civil Engineering and Building Technology (KICT) to develop a competitive structural system using the advantages of Ultra High Performance Concrete (UHPC). Three projects have been proceeding for the material technology of UHPC (K-UHPC), K-UHPC guidelines and the application of UHPC to a cable stayed bridge. Material and structural behavior of K-UHPC, its design guidelines, and domestic and international applications of UHPC to bridges in the projects are presented in this paper, including the world's first UHPC cable stayed roadway bridge at Chuncheon in Korea.

Keywords: UHPC, design guidelines, structural application, cable stayed bridge

1. Introduction

In spite of construction of many UHPC pedestrian and highway bridges since the first UHPC bridge in 1997 (Toutlemonde F. and Resplendino J. 2013), it is difficult to say they had competitiveness in the bridge market. From the economic point of view, the UHPC short or mid span bridges are probably less competitive than conventional concrete and steel composite bridges because of high initial construction cost, even though it could be more competitive according to (1) local and market conditions about the prices of materials such as sand, aggregate, and cement and (2) design conditions such as height, weight and under-clearance restrictions.

The competitiveness of UHPC, however, can be improved when it is applied to long span bridges such as cable stayed bridges. Application of UHPC to a concrete cable stayed bridge might accompany the reduction of self-weight of the superstructure by replacing heavy normal concrete sections with compact UHPC ones, which, in turn, results in the reduction of expansive cables and the size of foundation. Meanwhile, for the expensive sections of steel or composite cable stayed bridges, reasonable UHPC sections might be substituted without increasing the weight excessively, which, again, results in the reduction of the cost of the girders enough to compensate the minor increase of the cables and foundation cost.

But, simple substitution of UHPC for normal concrete and steel is not enough to get the best out of UHPC and to overcome its high cost. A new cable stayed bridge system combined with UHPC should be developed most effectively. Regarding this issue, this paper presents a series of KICT's research projects and UHPC bridge constructions to develop a competitive structural system using the advantages of UHPC including the world's first UHPC cable stayed roadway bridge.

2. R&D activities of KICT

2.1. Bridge 200

KICT developed UHPC material technology as a part of "Bridge 200", a 5-year research project (2002~2006) developing durable bridge systems (KICT 2012). The efforts to improve this technology and apply it to a bridge system led to the launch of the following research projects.

2.2. SUPER Bridge 200

KICT performed a 6-year research project called "SUPER Bridge 200" (2007~2012). This project dealt with the application of UHPC to a cable stayed bridge, and the meaning of "SUPER Bridge 200" is sustainable and safe, ultra-performing, pioneering, economic and environmental-friendly, remarkable bridge with 200-year service life. The main goal is 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 by combining UHPC and cable stayed bridge technology together. "SUPER Bridge 200" developed the technology for (1) the K-UHPC (the improved UHPC by KICT), (2) design and fabrication guidelines of K-UHPC structures, (3) a light and durable UHPC deck, (4) an economic UHPC cable stayed bridge system with the main span of 200 m ~ 800 m. During the project, many applications of K-UHPC were constructed such as; the first UHPC pedestrian cable stayed bridge (2009): the first UHPC highway bridge in Korea (2012). The details are discussed in the following sections.

2.3. SUPER Structure 2020

Following "SUPER Bridge 200", a 5-year research project called "SUPER Structure 2020" is on progress from December 2013. This deals with the application of UHPC and HPC (High Performance Concrete) developed by KICT, called as "SUPER Concrete", to civil and building structures including bridges, wind turbine towers, pontoon structures and etc. In terms of the bridge application, this project succeeds to the "SUPER Bridge 200". In this project, domestic and international K-UHPC bridges were constructed or is under construction as follows; the Hawkeye UHPC bridge in Iowa, USA (2015): the first UHPC highway bridge in Myanmar (2015), the first UHPC cable stayed roadway bridge called Chuncheon LEGOLAND Bridge in Korea (2015~2017)

3. Development of K-UHPC

The development of K-UHPC is focused on both minimizing the amounts of fiber (cost reduction) and maximizing the performance of UHPC. Blending macro fibers different in length can increase the tensile strength of UHPC while minimize the reduction in constructability due to long fibers (Fig. 1). Direct tensile test of the K-UHPC reveals strain hardening behavior after initial cracking, which is introduced in the design guideline (Fig. 2).

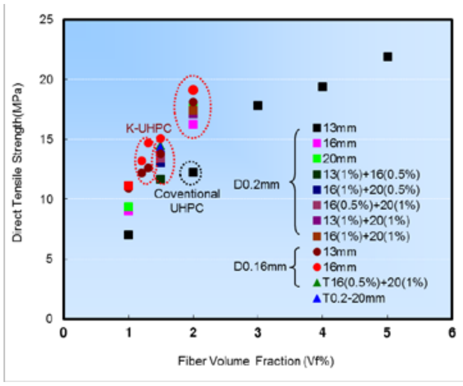


Figure 1. Tensile strength of K-UHPC

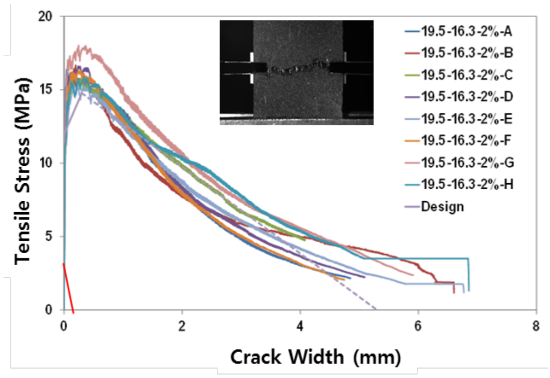


Figure 2. Tensile behavior of K-UHPC

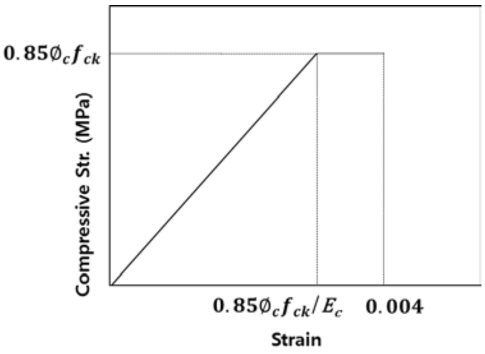
The basic K-UHPC composition developed by KICT is shown in Table 1. Steel fibers exhibit tensile strength higher than 2000 MPa and diameter of 0.2 mm, and the length shall be selected approximately among the values of 13 mm, 16 mm and 20 mm. K-UHPC specimens are steam cured for 48~72 hours at 90 degree after 24-hour curing at room temperature. The typical mechanical properties of the material are summarized in Table 2.

Table 1. K-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	0.018	1.5~2%

Table 2. Mechanical properties of K-UHPC

Design compressive strength	Design tensile strength	Elastic modulus	Poisson's ratio	Total shrinkage	Creep coefficient
180 MPa	10~13.0 MPa	45 GPa	0.2	600×10^{-6}	0.45



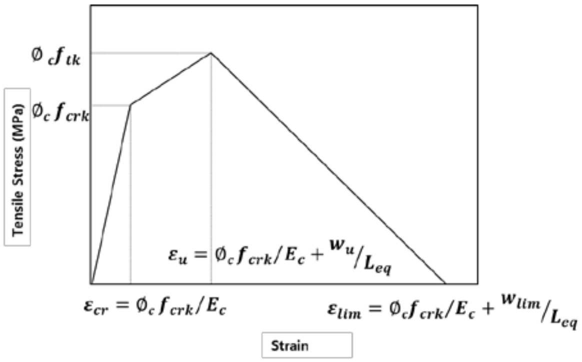


Figure 3. Compressive stress-strain curve **Figure 4. Tensile stress-strain curve**

Figure 3 and 4 show design compressive and tensile stress-strain curves proposed in the K-UHPC design guidelines. The strain hardening behavior observed in the tests is reflected in the tensile stress-strain curve (Fig. 4). The detailed description of the symbols used in the figures can be found in the K-UHPC design guidelines (KICT, 2014).

4. Structural behavior and design guidelines of K-UHPC members (SUPER Bridge 200 & SUPER Structure 2020)

In 2008 ~2012, the K-UHPC girders reinforced with rebars or tendons were tested to estimate the flexural strength and find how to estimate it for the design (Fig. 5) (Yang I.H. et al., 2010, Yang I.H. et al., 2011). It was done because, in spite of relatively high tensile strength of K-UHPC compared to conventional concrete, the large difference between compressive and tensile strengths of K-UHPC makes it necessary to use reinforcement in the UHPC flexural member such as a girder. In 2010, K-UHPC girders without shear stirrups were tested in shear (Joh C., et al., 2011). Test results showed that the sudden loss of the strength was not observed in spite of no shear reinforcement and the load was gradually increased with the propagation of the initial cracks to upper and lower flanges. 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. 6).

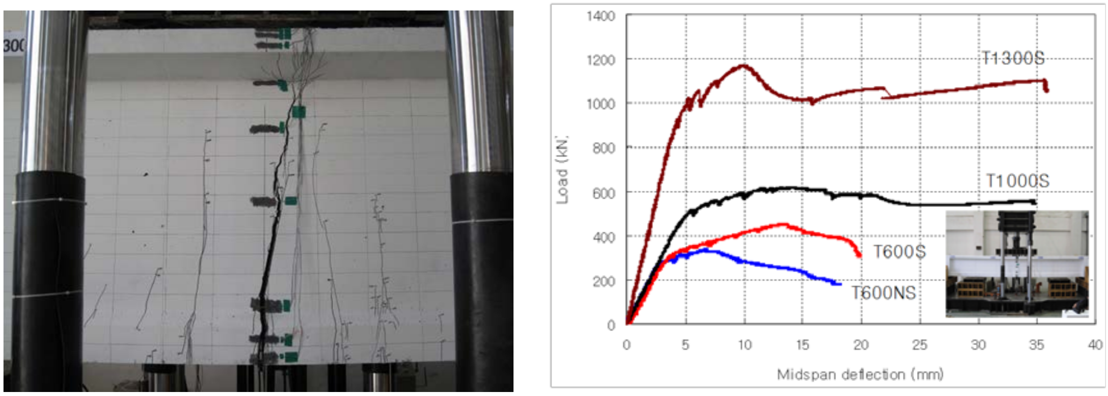


Figure 5. Flexural test and results of K-UHPC girders (Yang I.H. et al., 2011)

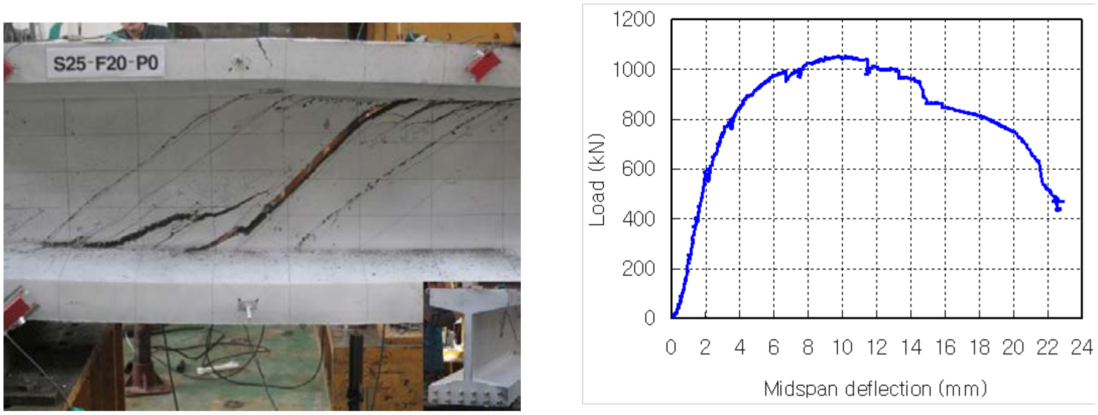


Figure 6. Shear test results of K-UHPC girders without stirrups (Joh C., et al., 2011)

Based on the test results, the K-UHPC design guidelines proposed the shear strength formula with an additional term ($V_{steel\ fiber}$) to consider the contribution of fibers after the initial cracks in the web (KICT, 2014).

K-UHPC girders were tested in torsion (Fig. 7). 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 K-UHPC.

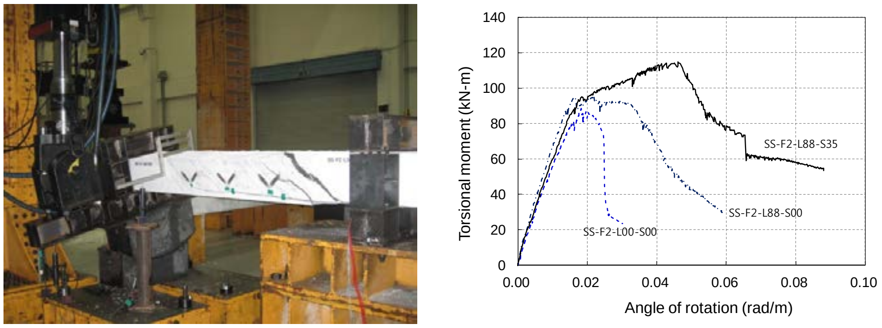


Figure 7. Torsional test and results of K-UHPC girders (Joh C. et al, 2012)

The test results show that the K-UHPC specimens with no reinforcement did not lose its torsional strength after cracking due to the ductility of K-UHPC, and the K-UHPC specimen with longitudinal rebars only also showed ductile behavior (Joh C. et al., 21012). The K-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 K-UHPC in the estimation of torsional strength of K-UHPC girders (eq. 1). The details of the terms used in eq. 1 can be found in the K-UHPC design guidelines (KICT, 2014).

$$T_n = T_s + T_{UHPC} = \frac{2A_0A_tf_{yv}}{s}cot\,\theta + 2A_0f_tt\,cot\,\theta \qquad (1)$$

Various tests were performed to allow the use of strands and rebars such as the minimum cover thickness, bond-slip relation, crack width and spacing, development length and etc. (Choi S. et al, 2015, Kim J. et al., 2015 and Kwahk I. et al., 2012). In general K-UHPC structures do not need the rebars (passive reinforcement) due to its own high and ductile tensile behavior, but, sometimes, the passive reinforcement is necessary to optimize the design. KICT also did punching tests of K-UHPC thin plates (Joh C. et al, 2008) for a punching formula and miscellaneous tests to optimize structural details such as shear keys. The design formulas based on the results of these researches are also proposed in the K-UHPC design guidelines (KICT, 2014).

The first draft of K-UHPC design guidelines was proposed in 2008 and has been updated yearly to include new research results (KICT, 2014). This guidelines referred to the design formulas from France (AFGC, 2013), Germany (Schmidt, M. et al, 2012) and Japan (JSCE, 2004).

One of the characteristics of this guidelines is the design formulas for the use of the passive reinforcement due to the reduced shrinkage of K-UHPC, which allows more economical design of K-UHPC structures.

5. Applications

5.1. UHPC Pedestrian Cable Stayed Bridge (SUPER Bridge 200)

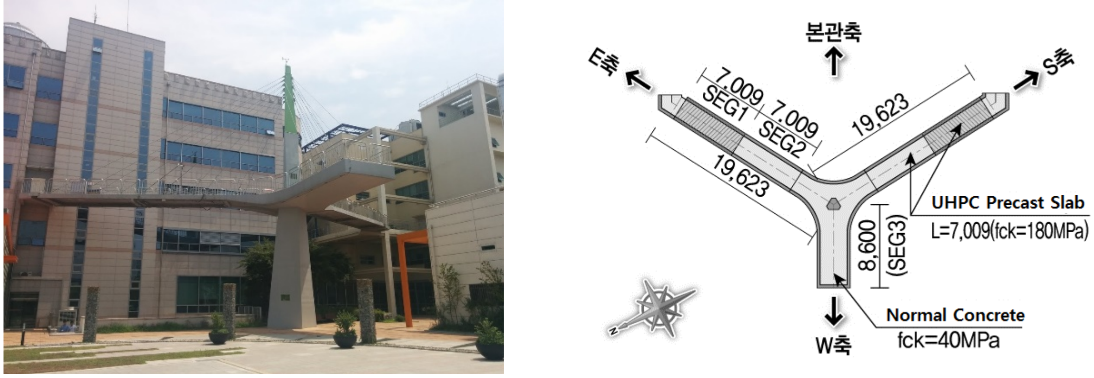


Figure 8. UHPC Pedestrian Cable Stayed Bridge Built at KICT

In 2009, an UHPC pedestrian cable stayed bridge (Fig. 8) was designed based on K-UHPC guidelines and constructed. This is the first UHPC pedestrian cable stayed bridge in the world, which verified the design and the elemental technologies for UHPC cable stayed bridge. Precast UHPC edge girders were used for two girders. Two precast girders were connected using steel bar after bonding with epoxy (KICT 2012).

5.2. Andong Bridge I and II (SUPER Bridge 200)

In 2012, the Andong Bridge I (Fig. 9), the first UHPC highway bridge in Korea, was built near Andong, Korea. The length and width of the bridge are 11 m and 5 m, respectively. The cross section of the UHPC girder was designed as the pi shape to use the maximum capacity of UHPC and no conventional reinforcement was used in the girders.

Figure 9. Andong Bridge I (π section)

Figure 10. Andong Bridge II (rib deck)

In late 2012, Andong Bridge II was erected to test a ribbed deck which comprises a part of superstructure in a cable stayed bridge (Fig. 10). This deck is lighter by 50% than the conventional precast concrete deck. The cost analysis revealed that the construction cost of the superstructure can be reduced by about 10% only by replacing the deck of the traditional steel composite cable-stayed bridge (Kim B-S. et al., 2016).

5.3. World's first UHPC Cable Stayed Roadway Bridge (SUPER structure 2020)

In 2015, with KICT, DAELIM Co., Ltd. has completed a design work for a new cable-stayed bridge using K-UHPC design guidelines for the deck with a span length of 100m (Fig. 11). The bridge is located at Chuncheon in Korea, and is being constructed for the LEGOLAND Korea which is Lego-themed children's/family theme parks, scheduled to open in 2017 with the construction cost of $330 million US dollars.

Figure 11. Bird's eye view of LEGOLAND UHPC Cable Stayed Roadway Bridge

The world's first UHPC cable stayed roadway bridge has an O-shaped single steel pylon with a diameter of 45m and a UHPC girder with a width of 29.5m and a height of 1.8m (Kim J-H. et al., 2016). Due to the UHPC, the cross section of the girder is able to be compact and optimized so that the girder can be 33% lighter than conventional concrete girder with 40MPa strength (Fig. 12 & 13). As a result, the amount of stay cables and foundation is reduced and the circular shaped pylon can be feasible. The girder comprises 52 segments with a length of 4 m, and will be fabricated and match-casted at a plant near the construction site.

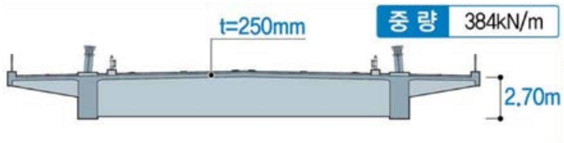


Figure 12. Normal concrete section

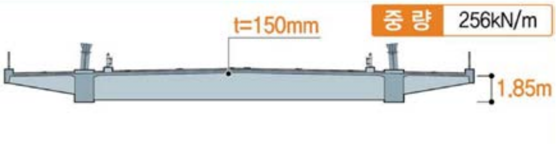


Figure 13. K-UHPC section

5.5. Applications of UHPC Road Bridge in USA and Myanmar (SUPER Structure 2020)

In the project of replacing the old bridge in Buchanan County, Iowa, Hawkeye UHPC bridge (Fig. 11(a)) was constructed using the K-UHPC and its design guidelines. Local cement and sand from Iowa were used with the premixing binder, admixtures and steel fibers from Korea. The length and width of the bridge are 15.9 m and 9.9 m, respectively. This project started with a great interest of the Iowa DOT in the economic efficiency of K-UHPC. Accordingly, successful construction of this bridge might lead to approval of the design and fabrication guideline of K-UHPC, and finally to the expansion of UHPC bridge constructions in Iowa.

Figure 14. Hawkeye UHPC Bridge in Iowa

Figure 15. Myanmar UHPC Bridge

In Myanmar, an UHPC bridge (Fig. 11(b)) was built to widen the shoulder of the existing bridge in the highway located between Yangon and Mandalay. This bridge used the K-UHPC made from the local materials such as cement and sand from Myanmar. This is the first UHPC highway bridge in Myanmar. Its length and width are 12.2 m and 8.3 m, respectively, and the cross section of the K-UHPC girder is designed as the π shape with no conventional reinforcement (Kim B-S. et al., 2015).

6. Conclusions

This paper presented KICT's intensive and systematic development of technology for a UHPC bridge since 2002. From the development of the UHPC material technology to the applications of UHPC to cable stayed bridge, the UHPC technology in KICT has been improved through three consecutive research projects, that is, "Bridge 200", "SUPER Bridge 200" and "SUPER Structure 2020".

In the projects, the K-UHPC design guidelines was developed based on the various tests and successfully applied to the UHPC bridges in Korea, USA and Myanmar. Specially the construction of the first UHPC cable stayed roadway bridge in the world is underway and will be accomplished in 2017. Based on these achievements, new horizon of UHPC application will be held actively.

7. References

Toutlemonde F. and Resplendino J., Proceedings of the RILEM-fib-AFGC International Symposium on Ultra-High Performance Fibre-Reinforced Concrete (UHPFRC-2013), Marseille, France, 2013

KICT, SUPER Bridge 200/Development of Economic and Durable Hybrid Cable Stayed Bridges, KICT, 2012.

KICT, Design Guidelines for K-UHPC, KICT, Korea, 2014.

Yang I. H., Joh C. and Kim B.S., "Structural behavior of UHPC beams subjected to bending", *Engineering Structures*, Vol. 32, 3478-3487, 2010.

Yang I. H., Joh C. and Kim B.S., "Flexural strength of large scale Ultra High Performance Concrete prestressed T-beams", *Canadian J. of Civil Engineering*, Vol. 38, pp. 1185-1195, 2011.

Joh C., Lee J., Yang I.H. and Kim, B.S., "Shear test of UHPC girders without stirrups", Proceedings of 9th Symposium on High Performance Concrete, New Zealand, 2011.

Joh C., Lee J., Yang I.H. and Kim, B.S., “Torsional test of UHPC square members”, Proceedings of 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials, Kassel, Germany, 2012.

Choi S., Joh C. and Chun S., “Behavior and strength of single cast-in anchors in Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) subjected to a monotonic tension or shear”, *KSCE Journal of Civil Engineering*, Vol.19, No. 4, pp. 964-973, 2015.

Kim J., Joh C. and Choi Y., “Load transfer test of post-tensioned anchorage zone in ultra high performance concrete”, *Engineering*, Vol. 7, pp. 115-128 (http://www.scirp.org/journal/eng), 2015.

Joh C., Hwang H., Choi E., Park J. and Kim B.S., “Punching Shear Strength Estimation of UHPC Slabs”, Proceedings of the 2nd International Symposium on Ultra High Performance Concrete, Kassel, Germany, 719-726, 2008.

Kwahk I., Lee J., Kim J. and Joh C., “Evaluation of the crack width of the Ultra High Performance Concrete (K-UHPC) structures”, *Journal of the Korean Society of Safety*, Vol. 27, No. 6, pp. 99-108 (in Korean), 2012.

AFGC, Ultra High Performance Fibre-Reinforced Concrete Recommendations, AFGC, 2013.

Japan Society of Civil Engineers (JSCE), Recommendations for Design and Construction of Ultra-High Strength Fiber Reinforced Concrete Structures (draft), JSCE, 2004.

B-S. Kim, C. Joh, S-Y. Park, J. Park (2016), “(Ultra) High Performance Concrete Cable Stayed Bridge Technology and Application”, Proceedings of EASEC-14 Structural Engineering and Construction, Jan 2016, Ho Chi Minh City, Viet Nam

J-H Kim, J. G. Yoon, H. S. Choi (2016), “The World’s First Adoption of UHPC for Cable-stayed Roadway Bridge”, Proceedings of EASEC-14 Structural Engineering and Construction, Jan 2016, Ho Chi Minh City, Viet Nam

B-S. Kim, C. Joh, S-Y. Park, J. Park (2015), “Case Studies Highlighting Innovative UHPC Bridge Applications of KICT”, Proceedings of 1st ACF Symposium, Oct 2015, Kolkata, India

8. Acknowledgements

This research was supported by a grant (13SCIPA02) from Smart Civil Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport (MOLIT) of Korea government and Korea Agency for Infrastructure Technology Advancement (KAIA).