# APPLICATION OF UHPC FROM PEDESTRIAN CABLE-STAYED BRIDGE TO THE FIRST UHPC CABLE-STAYED ROADWAY BRIDGE

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**Abstract**

After 2002 marking the start of the development of a brand-new ultra-high performance concrete (UHPC), namely K-UHPC, for the advancement of related technology and field-application, the Korea Institute of Civil Engineering and Building Technology (KICT) has restlessly improved the technological features and economic efficiency of K-UHPC to open and extend its range of application. This paper reviews briefly application examples of K-UHPC to bridges and buildings and gives details on the forthcoming UHPC roadway bridge under erection since 2015 at the entrance of Legoland in Chuncheon, Korea. At its completion previewed at the end of 2017, Legoland Bridge with a total length of 966 m including a cable-stayed bridge of 200 m will be the first of its kind ever built in the world. This very first UHPC roadway cable-stayed bridge will be a revolution in the history of bridge and will bear a particular meaning since, unlike previous UHPC bridges, its construction was selected through general bidding process.

**Résumé**

L'année 2002 a marqué le début du développement d'un nouveau type de béton fibre à ultra-hautes performances (BFUP), dénommé K-UHPC, en termes de recherches liées à cette technique et à son application. Depuis, l'institut Coréen du Génie Civil et de la Construction (KICT) n'a cessé d'améliorer les performances techniques et l'économie du K-UHPC pour permettre et étendre ses applications. L'article passe en revue les applications du K-UHPC à des ponts et bâtiments et détaille le projet de pont routier en BFUP en construction depuis 2015 à l'entrée de Legoland à Chuncheon en Corée. Lors de son achèvement prévu en 2017, le pont de Legoland, d'une longueur totale de 966 m et comprenant un pont haubané de 200 m, sera le premier de ce type au monde. Ce tout premier pont routier haubané en BFUP constituera une révolution dans l'histoire des ponts et revêtira un enjeu particulier car, au contraire des précédents ponts en BFUP, sa construction aura été sélectionnée au terme d'un appel d'offres général.

# 1. INTRODUCTION

After the start of the development of a brand-new ultra-high performance concrete (K-UHPC) in 2002 for the advancement of related technology and field-application, the Korea Institute of Civil Engineering and Building Technology (KICT) has restlessly improved the technological features and economic efficiency of K-UHPC to open and extend its range of application. In 2009, KICT erected the first UHPC footbridge followed by the consideration of a UHPC roadway cable-stayed bridge for the turnkey design of a sea-crossing long-span bridge in the Southern coast of Korea in 2011 and the construction of the first UHPC roadway bridge in Korea in 2012 (KICT, 2012). Thereafter, KICT pursued R&D and succeeded in improving the price-competitiveness by reducing the material cost of UHPC. Moreover, KICT led informative campaigns to promote actively UHPC to the ordering and contracting parties in Korea and overseas. These efforts resulted to the completion of Hawkeye UHPC Bridge in Iowa, USA, Ka Thae Myaung Bridge, Myanmar, in 2015, and the first application of a UHPC roadway cable-stayed bridge that will soon give entrance to Legoland Theme Park in Chuncheon, Province of Gangwon, Korea.

As part of the Legoland Construction Project and standing at the entrance of the access road linking the mainland to the island hosting the park, Legoland Bridge will be a gateway that will be crossed by all the visitors. The Provincial Office of Gangwon, which ordered the construction project, requested the bridge be designed to render the pleasure, imagination and creativity featured by Legoland Theme Park. UHPC cable-stayed bridge was selected to accommodate the original shape of the pylons by exploiting the advantages of UHPC for the lightened superstructure and slender members. The high durability provided by the adoption of this material was also decisive in the selection of the bridge owing to the resulting extended lifetime and minimized maintenance of the structure. The most determinant reason for the selection of the UHPC cable-stayed bridge was the quasi-absence of increase in the construction cost when using UHPC instead of normal concrete revealed by the economic analysis performed during the proposal of the bridge. The construction of the access bridge to Legoland Park with a total length of 966 m of which 200 m for the cable-stayed section started in July of 2015 and its completion is expected at the end of 2017.

This paper reviews briefly K-UHPC bridge and building achievements in Korea and gives details on the forthcoming UHPC roadway bridge under erection since 2015 at the entrance of Legoland.

# 2. APPLICATION OF KOREA

## 2.1 UHPC Pedestrian Cable-stayed Bridge

A UHPC cable-stayed footbridge was designed and erected in 2009 to link buildings within KICT site through the “SUPER Bridge 200” project. Being the first UHPC footbridge in the world, this bridge was planned as test bed to verify the design and elementary technologies developed for the erection of UHPC pedestrian bridges. As shown in Fig. 1, two precast UHPC edge girders were employed. These girders were fabricated by match casting and interconnected by epoxy-coated steel bars. Since the construction of the cantilevered sections was the most critical part of the erection, the cantilevered structures were designed without connecting the girders to the buildings so as to examine the safety in case of large-scale bridges. Tuned mass dampers (TMD) were installed to control the deflection and acceleration in service, and cast-in-place joints were adopted for the connection around the pylon.

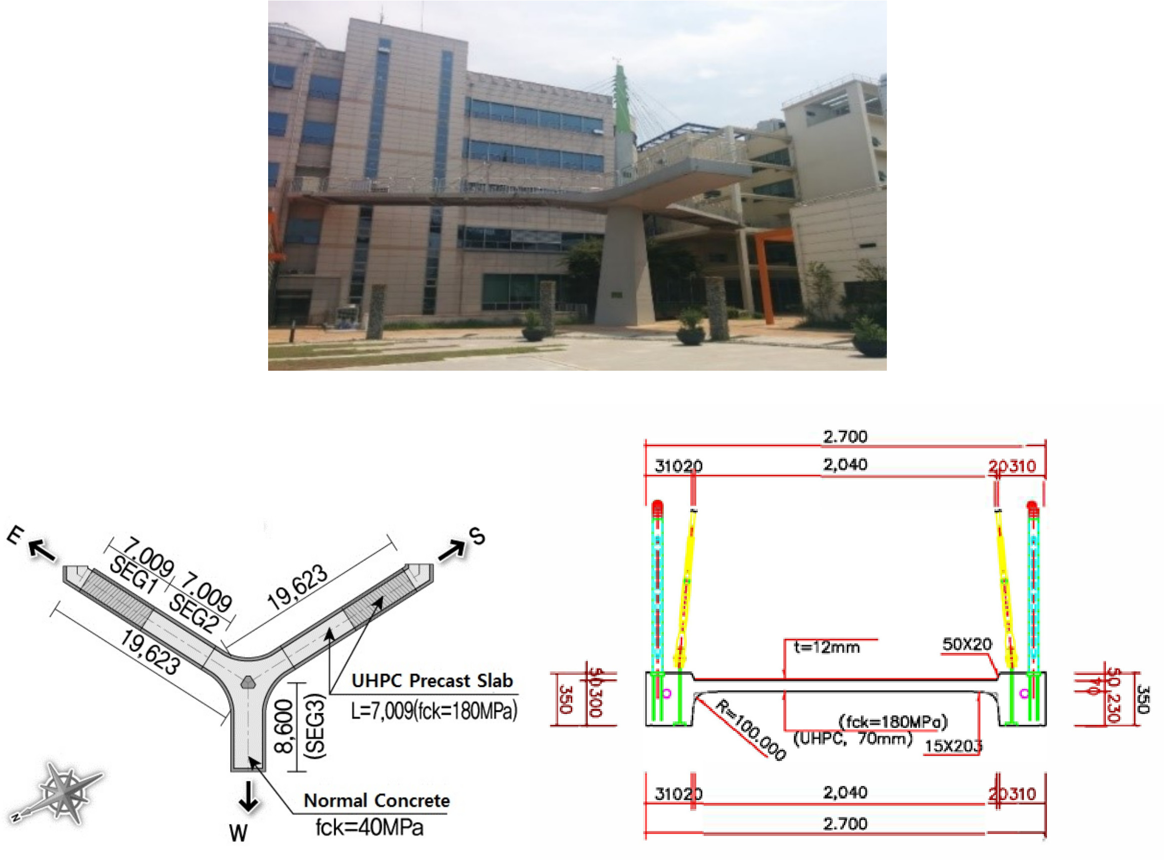



Figure 1: UHPC pedestrian cable-stayed bridge built at KICT [1]

## 2.2 Design of Jobal Bridge

In 2011, a major Korean construction company, Daelim E&C, submitted the design of UHPC cable-stayed bridge for the turnkey bidding of Jobal Bridge linking the islands of Jobal and Dunbyung in the Southern cost of Korea. Fig. 2 presents a rendering of Jobal Bridge that was designed using the technologies developed by the “SUPER Bridge 200” project. As shown in Fig. 3, the design proposed a 3-pylon UHPC cable-stayed bridge with main span of 200 m, pylon height of 90 m and edge girder superstructure made of UHPC. This proposal is the first UHPC roadway cable-stayed bridge designed in the world.

Figure 2: Rendering of Jobal Bridge [2]

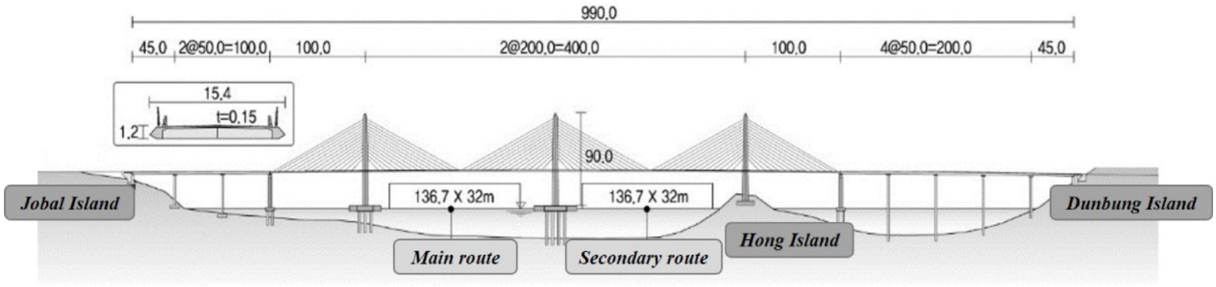



Figure 3: Side plan of Jobal Bridge [2]

### 2.3 The First UHPC Highway Bridge in Korea

Summer of 2012 witnessed the construction of the first UHPC road bridge in Andong, a city renowned for its historical background. The bridge was designed with the smallest scale enabling to verify the field-applicability of the UHPC material and bridge technology developed by KICT. Three π-shaped girders of which each of the two ribs was equipped with 7 strands were prefabricated in a batch plant and transported on site. The bridge itself has a span length of 11 m and a width of 5 m with a deck thickness of only 100 mm. The total depth of the girder including the deck is 600 mm leading to a weight of 112 kN per girder, which required small-sized transportation and construction equipment, and enabled to ease significantly the construction works. The 3 girders were installed on site using a small-sized crane. Prestressing was applied to achieve the monolithic structure after the joints of the girders were cast-in-place using a mobile UHPC mixer. Considering that similar construction process can be applied regardless of the size of the bridge, this successful erection proved sufficiently the field-applicability of the technology.

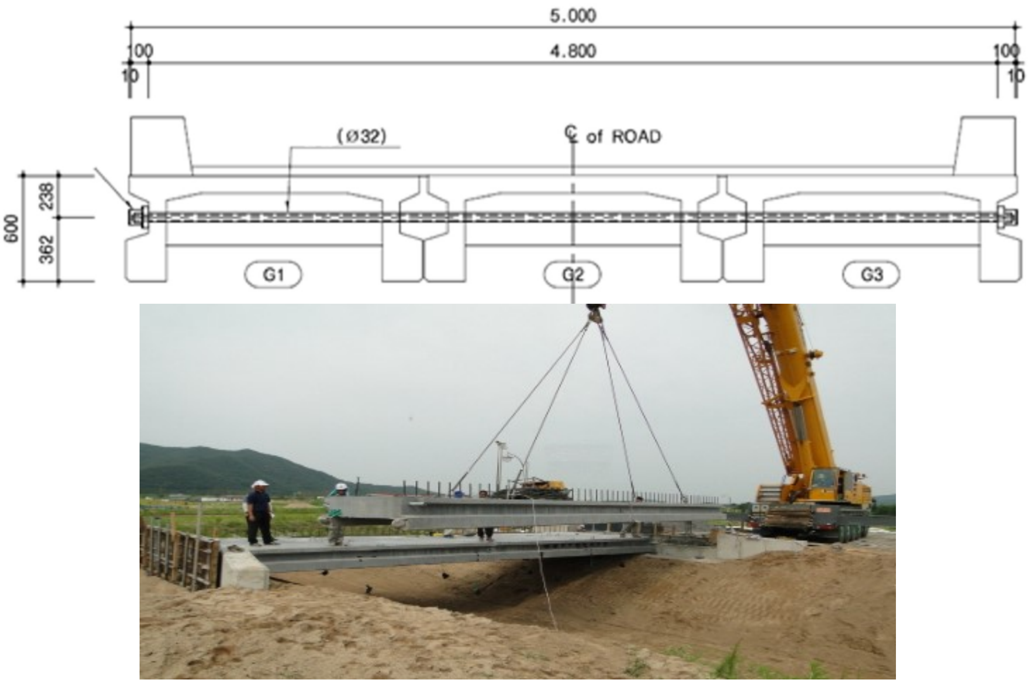



Figure 4: Cross section and installation of the first UHPC road bridge in Korea

### 2.4 Hawkeye UHPC Bridge in Buchanan County, Iowa, USA

In 2015, highway bridges using the UHPC technology developed by KICT were constructed overseas in USA and Myanmar. The first overseas application took place in Buchanan County, Iowa, USA, for the replacement of a bridge built in 1950s. To that goal, the mix composition of UHPC using local cement and sand was derived and the corresponding performances were examined through various tests. The afore mentioned π-shaped cross section already applied in Korea was adopted to achieve the bridge with span length of 16 m and width of 10 m. A total of 6 π-shaped girders were precast and the erection was conducted following a process similar to the one used for the UHPC bridge in Andong. The noticeable difference with Andong was the use of the drum mixer of the ready-mix truck instead of the batch plant with a separate mixer for the fabrication of UHPC. In this site, a total volume of 8.4 $m^3$ of K-UHPC per girder was mixed using two 4.2 $m^3$ ready-mix trucks. This experience widened the applicability range of UHPC since the fabrication, transportation and placing of UHPC could be realized by means of ready-mix trucks in a site with very minimal working space that cannot accommodate a batch plant.

Figure 5: Ready-mix truck for the fabrication of UHPC girders and view of the completed bridge

### 2.5 Ka Thae Myaung Bridge in Myanmar

In November of 2015, KICT and the Ministry of Construction of Myanmar constructed conjointly the Ka Thae Myaung Highway Bridge, the first UHPC bridge in Myanmar that applied the KICT's technology for the enlargement of a bridge located at the 168-mile post along the Yangon-Mandalay Highway. The bridge has a length of 12.2 m and a width of 8.3 m. The structural constraint was to connect directly the new UHPC bridge to the existing bridge that had normal concrete girders. Therefore, the UHPC girders were fabricated to have height much larger than necessary to reduce the difference in stiffness between the old and new bridges at the joints. Local cement and sand were used to verify the applicability of UHPC in Myanmar. Especially, compressive strength higher than 150 MPa could be achieved by mixing and placing UHPC using ready-mix trucks. Fig. 6 shows the π-shaped cross section of the bridge and a view of the completed bridge.

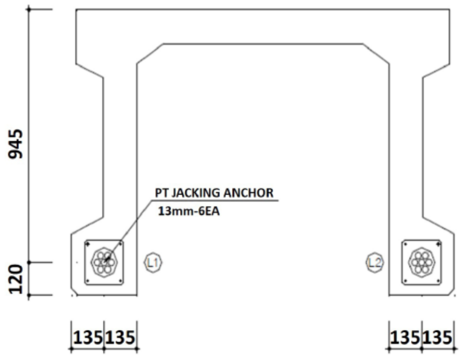



Figure 6: Cross section and view of the first UHPC highway bridge in Myanmar

Figure 7: Bird's eye view of Hotel Healing Place in Korea

### 2.6 Hotel Healing Place at Ulung Island, Korea

The construction of a hotel applying 120-MPa UHPC started on July of 2016 in Ulung Island, Korea, and is expected to finish in July of 2017. As shown in Fig. 7, the hotel has two buildings of which building A is a 13.4-m high two-story structure and building B is a 6.0-m high single-story building. The realization of these two buildings presenting complex but exquisite shape will require 460 m$^3$ of UHPC using local cement and sand. The curved forms were designed considering the fluid pressure, and organic fiber is adopted to provide fire resistance. Ready-mix equipment and ready-mix trucks are employed concurrently to fabricate UHPC considering the local insular conditions of the site. Placing is performed by pumping and general curing is done instead of high temperature curing. Once completed this hotel will be the first UHPC shell structure ever built in the world representing a major foothold for further applications to architectural works.

### 2.7 Remodeling Plan of HANA Bank Building Façade, Korea

In 2016, plan was devised to apply UHPC as skinning material of building structures. A prototype was fabricated to verify the applicability of UHPC as skinning material with the thin and complex shape shown in Fig. 8 and confirmed the fabricability and structural performance of the façade. Unfortunately, the design was not applied but opened promising application in the near future.

Figure 8: Rendering of remodeled HANA bank building façade and prototype specimen


Figure 9: Memorial monument for the 50th anniversary of KAIST (2016)

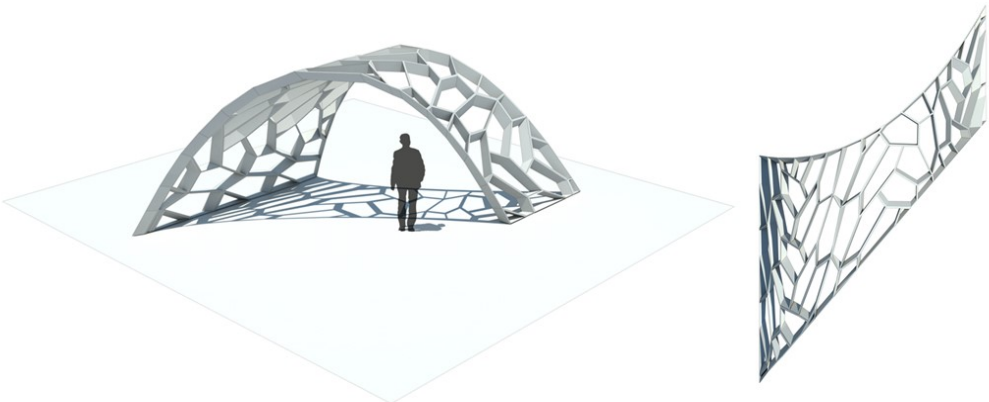


Figure 10: UHPC modular pavilion for the library at Seoul National University (2017.06)

### 2.8 Monumental UHPC Structure with Character Holes and Plain UHPC Atypical Architecture

UHPC was applied in 2016 to build the monument commemorating the 50th anniversary of the Korea Advanced Institute of Science and Technology (KAIST) in Daejeon, Korea (Fig. 9). This monument represented the very first attempt using concrete to achieve a structure moulded with character holes. To that goal, the latest curing and moulding technologies of UHPC were applied to secure the quality of the finished work.

June of 2017 will see the completion of the pavilion celebrating the new library at Seoul National University. This pavilion is formed by 57 UHPC modules presenting different shapes (Fig. 10). Sample modules were fabricated after having developed modelling technology of the form for each module and fabrication technology of the forms. This pavilion is the first example of modular and atypical structure made of plain concrete. This forthcoming structure is expected to demonstrate the exemplarity of the automated design and construction technology for atypical structures.

## 3. CHUNCHEON LEGOLAND BRIDGE

### 3.1 Specifications

The bridge giving access to Legoland Theme Park includes a central UHPC cable-stayed bridge with steel composite bridges at both sides. Fig. 11 presents the plans of the main cable-stayed bridge which has one pylon and two spans. The major design specifications of the bridge are listed in Table 1. Table 2 arranges the mechanical properties of UHPC applied for the superstructure.

Table 1: Major design specifications of Legoland Bridge

| | |
|---|---|
| Bridge type | 1-pylon UHPC cable-stayed bridge (class 1) |
| Span composition | L = 2@100 m = 200 m |
| Superstructure type | UHPC edge girder |
| Substructure type | Circular steel pylon, cast-in-place piles |
| Construction method | Bent method |
| Bridge width | B = 29.5 m (4-lane two-way road, cycle lane) |

Table 2: Mechanical properties of UHPC

| Design strength | | Stress limits | | Elastic modulus | Poisson's ratio | Thermal expansion coefficient |
|---|---|---|---|---|---|---|
| Compr. | Tension | Compr. | Tension | | | |
| 180 MPa | 13 MPa | 108 MPa | 10.4 MPa | 45 GPa | 0.2 | $11\times10^{-6}$ /°C |

### 3.2 Design Guideline and Structural/Financial Benefits of UHPC

The access bridge to Legoland is currently (April, 2017) under construction. In concern with the cable-stayed bridge section, the circular pylon is near to completion, and half of the UHPC stiffening girders has been precast and will be installed in April of 2017.

The access bridge was designed in compliance with the limit-state design method of the Korea Highway Bridge Design Code (2015). The design of the UHPC stiffening girders used in the cable-stayed bridge section was conducted with respect to the "Structure Design Guideline of Ultra High Performance Concrete (K-UHPC)" published by the Korea Concrete Institute (2012). The fabrication of UHPC applied the specifications including the range of application, referred standards, constitutive materials, mix composition, fabrication method, member fabrication method and quality control (KICT, 2015).

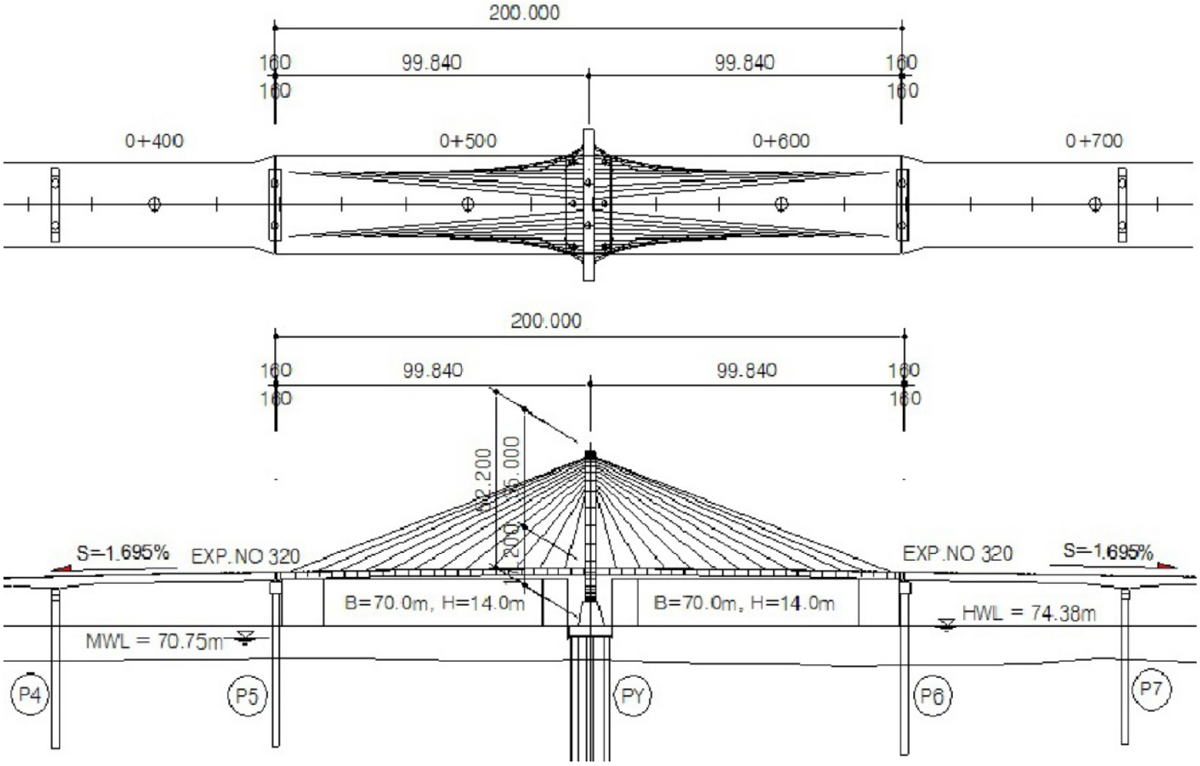



Figure 11: Plans of access bridge to Legoland Theme Park (Daelim E&C, 2015)

Figure 12: Rendering and current view of access bridge to Legoland (Daelim E&C, 2015)

The design guideline and specifications of K-UHPC were validated through various material and structural tests performed by KICT. Moreover, two full-scale specimens were fabricated and assembled to verify in advance the constructability and workability of the precast edge girder applied in the bridge. A wheel tracking machine simulating actual wheel loading was also used to conduct rolling fatigue test and examine the durability of the girder (Fig. 13).

Fig. 14(a) presents the cross-section of the UHPC stiffening girder including the edge girders, deck and cross-beams. The cross beams are spaced at intervals of 4.0 m corresponding to the unit length of the segments and the assemblage is strengthened by transverse prestressing. In order to use efficiently the cross section, the thickness of the cross beams was set to only 150 mm at the exception of the bottom at which the tendons are disposed. For the deck, the thickness is 150 mm in the roadway part and 100 mm in the pedestrian part. The span length of the deck is 4 m. The deck, edge girders and cross beams are fabricated monolithically, and dry joint is chosen to connect the segments so as to prestress the girders and deck separately. Bundles of five 15.2-mm strands are disposed at intervals of 950 mm for the connection between the decks and tensile strengthening. The joints between the segments is done by match-casting, and the performance of the joints is secured by means of shear keys.

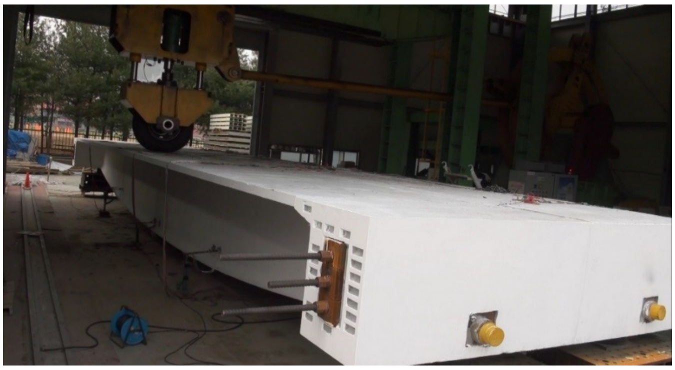
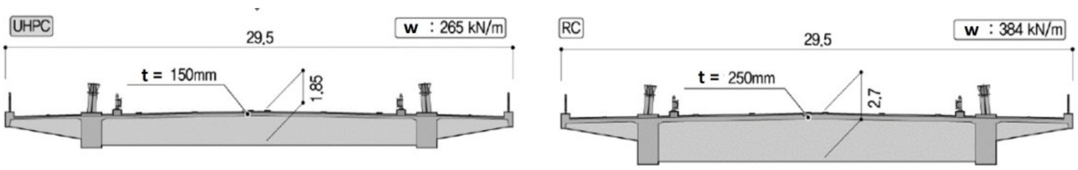


Figure 13: Rolling fatigue test of 800-m class UHPC cable-stayed bridge prototype (2011)




(a) UHPC ($f_{ck}$=180 MPa) (b) Normal concrete ($f_{ck}$=40 MPa)

Figure 14: Comparison of design alternatives of edge girder according to adopted material (Daelim E&C, 2015)

Compared to normal concrete (40 MPa, Fig. 14(b)), the application of UHPC to the stiffening girder reduces the thickness of the deck by 40%, the depth of the girders by 31%, and the weight of the structure by 33%. Such lightening of the superstructure enables to achieve the circular pylon, which figures the gateway to Legoland Theme Park (Fig. 12). Furthermore, the lightweight superstructure offers also significant advantage in the operation of the construction equipment like the bent. Owing to these benefits, it appeared that there is practically no increase in the construction cost following the application of UHPC instead of normal concrete despite of the high cost of UHPC.

### 3.3 Material Features

The components of UHPC can be classified into premixing binder, aggregates, liquid materials and steel fibre. The premixing binder involves cement, mineral admixtures and other performance-improving agents. Note that it is not necessary to use the premixing binder on site and that each material can be introduced according to the prescribed process and dry-mixed considering the conditions on site. The sand shall in principle have grain size smaller than 0.5 mm and have more than 90% of SiO2. When another type of sand is used, preliminary test shall be conducted to verify if the performance of UHPC is satisfied. The liquid materials include water, superplasticizer (SP), shrinkage-reducing agent (SRA) and antifoaming agent. The steel fibres shall basically develop tensile strength higher than 2,000 MPa and have diameter of 0.2±0.02 mm. In addition, steel fibre shall be admixed to achieve volume fraction to concrete of 0.5% for fibre length of 16±0.5 mm and 1.0% for fibre length of 20±0.5 mm.

The mix proportions of UHPC shall be decided considering the adopted materials, the condition of the member at hand, and the curing and environmental conditions. Table 3 lists the standard mix proportions for UHPC applied to the access bridge to Legoland (KICT, 2015). The fluidity and air content of the mix was determined with respect to the shape, dimensions, inclination, alinement and aesthetic appearance of the member. For the fabrication of the stiffening girder, the target slump flow and air content are respectively 700±100 mm and 4.5±1.5%.

Table 3: Mix proportions of UHPC (unit mass in kg/m$^3$)

| Water | Cement | Premixing binder | Sand | Steel fiber | | SP | SRA |
|---|---|---|---|---|---|---|---|
| | | | | 16 mm | 20 mm | | |
| 197.1 | 788.5 | 473.1 | 867.4 | 39 | 78 | 18.1 | 7.98 |

## 4. CONCLUSIONS

KICT poured efforts for the advancement of technology and field-application related to UHPC since 2002. After 15 years of restless research, KICT succeeded in improving significantly the performance and economic competitiveness of the material and played a leading role in its commercialization and application on field. A major achievement is the selection of the UHPC cable-stayed bridge with its circular pylon as gateway to Legoland Theme Park in Chuncheon, Korea. This circular pylon could be designed by exploiting fully the advantages of UHPC which enabled to reduce the depth of the girders by more than 31% and the weight of the superstructure by more than 33% compared to normal concrete. Technically speaking, the selection of this bridge also paid attention to the extended lifetime and durability provided by the adoption of UHPC. After its successful completion at the end of 2017, Legoland Bridge will be the first UHPC roadway cable-stayed bridge ever built in the world. This very first UHPC roadway cable-supported bridge will be a revolution in the history of bridge and will bear a particular meaning since, unlike previous UHPC bridges, it was selected through general bidding process. This experience will undoubtedly boost further application of UHPC in future bridge construction projects.

## ACKNOWLEDGEMENTS

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