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APPLICATION OF ULTRA-HIGH PERFORMANCE CONCRETE TO PEDESTRIAN CABLE-STAYED BRIDGES

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Abstract

The use of ultra-high performance concrete (UHPC), which enables reducing the cross sectional dimension of the structures due to its high strength, is expected in the construction of the super-long span bridges. Unlike conventional concrete, UHPC experiences less variation of material properties such as creep and drying shrinkage and can reduce uncertainties in predicting time-dependent behavior over the long term. This study describes UHPC's material characteristics and benefits when applied to super-long span bridges. A UHPC girder pedestrian cable-stayed bridge was designed and successfully constructed. The UHPC reduced the deflections in both the short and long term. The cost analysis demonstrates a highly competitive price for UHPC. This study indicates that UHPC has a strong potential for application in the super-long span bridges.

Keywords: UHPC, Time-dependent behavior, Cable-stayed bridges.

1. Introduction

Within the last few decades, researchers have been studying ultra-high performance concrete (UHPC). This advanced material shows great potential to improve infrastructure performance. UHPC now needs to make the transition from research and development to actual construction uses [1, 2]. Because the application of UHPC to real-world projects has been slow, UHPC usage needs to be promoted in the construction industry. The purpose of this study was to present a case study of UHPC application in order to accelerate UHPC usage in the construction industry [3, 4]. UHPC was successfully implemented on a large scale in a pedestrian cable-stayed bridge structure in South Korea. UHPC was found to effectively extend the span length of the bridge structure due to its high strength and minimal long-term variation of material properties. UHPC shows excellent potential in extending the span length of bridge superstructures.

2. Material Characteristics of UHPC

Ultra-high performance concrete (UHPC) is a high-strength material created by combining Portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water, and steel or organic fibers [1, 3-5]. A cementitious composite material composed of an optimized gradation of granular constituents, UHPC's water-to-cementitious materials ratio is less than 0.25; it has a high percentage of discontinuous internal fiber reinforcement. UHPC provides compressive strength up to 200 MPa. The material characteristics of UHPC can be summarised as follows [1, 3, 5]:

- Ultra-high strength through the exclusion of coarse aggregates.
- Uniform material properties and satisfactory particle distribution.
- Formation of remarkable micro-structure created with high-temperature steam curing.
- Remarkable reduction in drying shrinkage due to high-temperature steam curing
- Increased toughness through the addition of steel fibers.

Table 1 summarizes the typical compositions of concrete materials at different levels of performance [3]. While ordinary and high performance concrete consist of cement, fine and coarse aggregates, and admixtures, UHPC is made up of cement, fine aggregates, admixtures, steel fibers, and nano-fillers. The coarse aggregate was replaced in UPHC with steel fibers and nano-fillers that enhance the mechanical strength of UHPC. The nano-filler increased not only compressive strength but also tensile strength [3, 5, 6].

Given this variety of excellent material properties, UHPC can yield the following advantages when applied to bridge structures [5-7]:

- Reduction of the cross sectional area, which decreases self-weight (dead load).
- Extension of service life due to outstanding durability.

Table 2 summarizes UHPC's material properties as developed by the Korea Institute of Construction Technology (KICT) [3, 4]. These properties were present in the UHPC used in the construction of the pedestrian cable-stayed bridge in the study.

Table 1. Compositions of Concrete Materials at Different Levels of Performance.

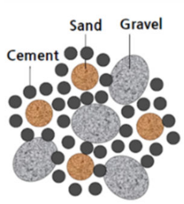
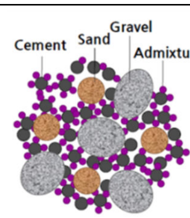
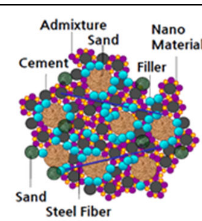
Ordinary Performance Concrete	High Performance Concrete	Ultra-High Performance Concrete
		
Strength : 20–40 MPa Porosity : 10–20%	Strength : 50–100 MPa Porosity : 5–8%	Strength : 150–300 MPa Porosity : 2% below

Table 2. Material Properties of UHPC by KICT.

Characteristics	Values
Design compressive strength	180 MPa
Design tensile strength	10 MPa
Elastic modulus	52,000 MPa
Unit density	25.5 kN/m^3
Possion ratio	0.2
Drying shrinkage	100×10^{-6}
Creep coefficient	0.2
Thermal expansion	12×10^{-6}/°C

3. Design of UHPC Girder Pedestrian Cable-Stayed Bridge

3.1. Overview of pedestrian cable-stayed bridge

Figure 1 shows the pedestrian cable-stayed bridge constructed in South Korea. UHPC material was applied to the two front girders in the bridge, and ordinary performance concrete (OPC) was used in the rear girder and other parts in the bridge. KICT constructed the bridge to better understand the limitation of current design methods and document the real-world application of UHPC in super-long span bridges [3, 4].

The bridge's design and construction took place under the following constraints:

- Girder thickness of less than 750 mm
- Use of hybrid structures consisting of OPC and UHPC
- Connection between existing and new buildings
- Non-transfer of self-weight of the bridge to existing buildings
- Verticality of one pylon surface due to constructability
- Avoidance of underground obstacle.

The short-term and long-term behavior of the bridge was numerically predicted using such software as 3D-series [8] which had been used for analysing the structural behavior of various types of bridges.

Fig. 1. UHPC Girder Pedestrian Cable-Stayed Bridge.

3.2. Design of girder thicknesses

As shown in Fig. 1, the deck in the bridge consisted of two front girders and one rear girder. The material used in the girders was determined by the constraints mentioned earlier. The two front girders were constructed with UHPC and the rear with OPC. The required strength of each girder suggested the thicknesses used: 70 mm of UHPC and 180 mm of OPC.

Figure 2 shows the P-M interaction diagram of the bridge's OPC and UHPC girders, indicating that the flexural strength of the UHPC girder was less than the OPC girder's. This difference occurred because the OPC girder was thicker than the UHPC girder. However, the factored bending moment of UHPC girder was much smaller than that of the OPC girder, indicating that the UHPC girder satisfied the strength design requirement with enough safety margin. One of UHPC's featured material properties-its ultra-high strength-reduced the thickness of the deck, which thus decreased the self-weight of the entire structure.

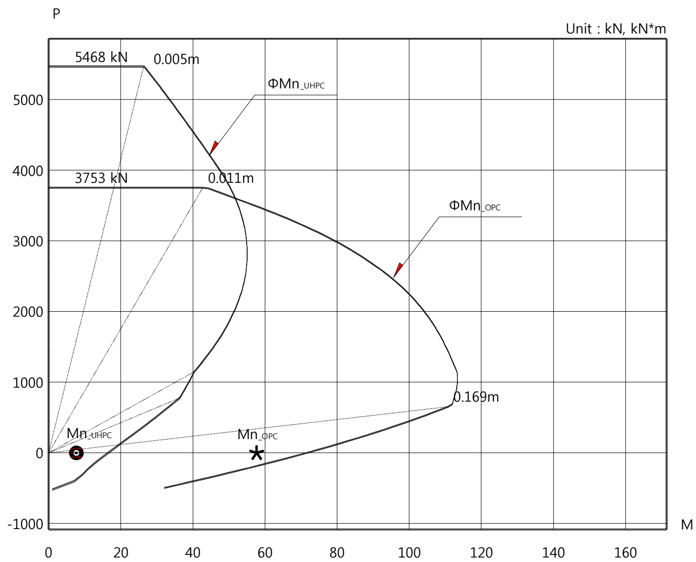
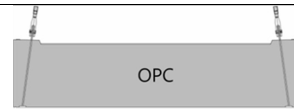
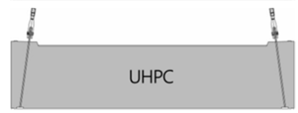


Fig. 2. P-M Diagrams of OPC and UHPC Girders.

3.3. Deflection of girders

The bridge was required to connect existing buildings to new buildings without transferring any loads to the buildings themselves. Therefore, the bridge girders were supported by the pylon, with no other support provided, as shown in Fig. 3. Because the UHPC reduced the thickness and the corresponding self-weight of the girders, the structural behaviors (including the deflections) varied when materials with different levels of performance were used in the front and rear girders, as shown in Table 3. Figure 4 shows the overall deflection of the bridge when UHPC was used for the front girders and OPC used for the rear girder (a partial UHPC application). The different thicknesses of the girders produced the unbalanced deflection illustrated in Fig. 4. The OPC girder was thicker and heavier than the UHPC girder. This unbalanced self-weight produced the unbalanced deflection, which was increased over the long term by such time-dependent properties as creep and drying shrinkage [9].

Table 3. Applications of OPC and UHPC to Girders.

	Front girder	Rear girder
OPC application		
Partial UHPC application		
Full UHPC application		

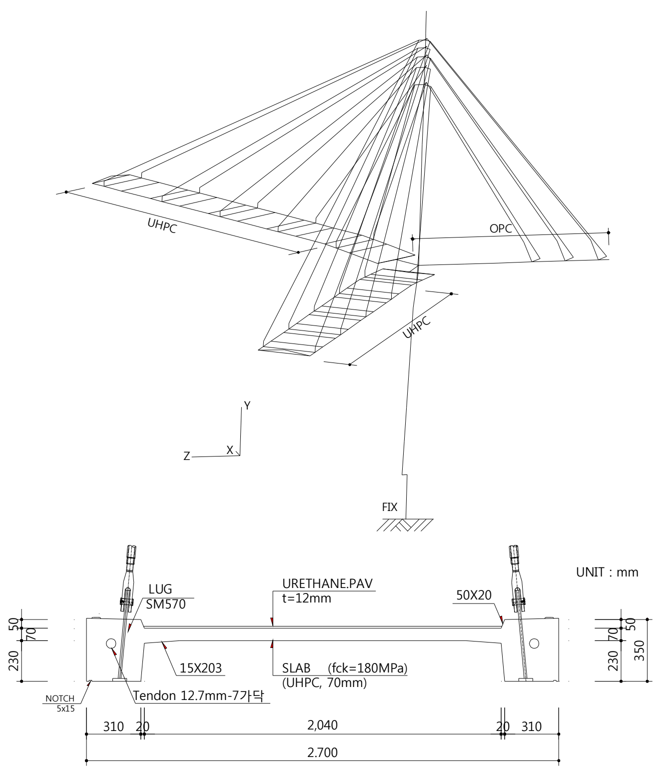


Fig. 3. Modeling of the Structural System and a Typical Section of the Girder.

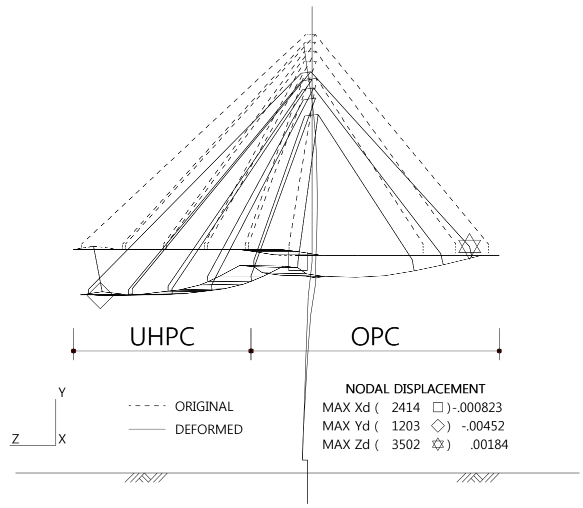


Fig. 4. Typical Deflection of the Girders.

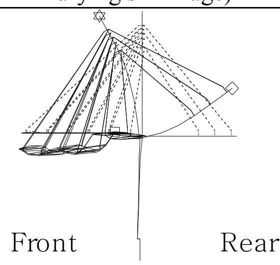
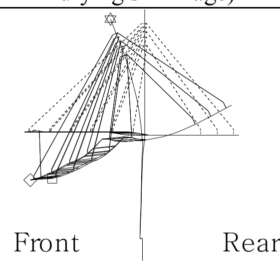
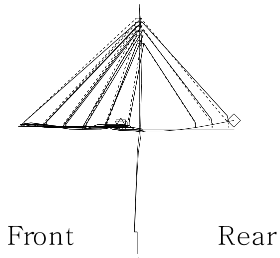
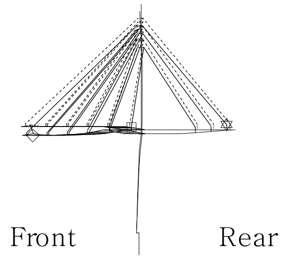
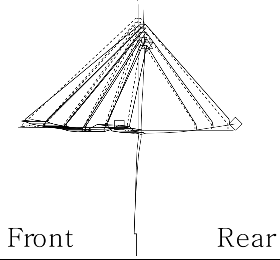
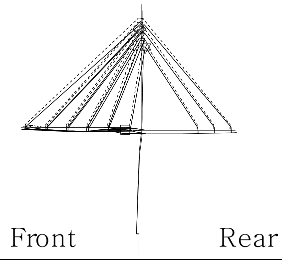
Table 4 shows the overall deflections before and after considering creep and drying shrinkage when concrete with different levels of performance was applied as shown in Table 3. The time-dependent behavior including the deflection was numerically predicted using the software as 3D-series [8]. The time-dependent deflection was calculated at 30 years. Figure 5 illustrates the distribution of the deflection along with the distance from the center pylon. The girders with full UHPC application demonstrated smooth deflection because their self-weight was balanced. While the front girders in the partial UHPC application were slightly inclined downward, however, the difference in the deflections between the front and rear girders was not significant. The OPC application, which includes OPC used both for front and rear girders as shown in Table 3, produced considerable downward deflection in the front girder, which was increased by creep and drying shrinkage over the long term.

Figure 6 shows how the unbalanced self-weight of the girders affected the long-term deflection of the bridge when the partial UHPC was applied. The behavior consisted of the following five developments:

- Upward deflection in the rear OPC girder due to creep and drying shrinkage
- Movement of back stay cable
- Movement of pylon
- Transfer of front stay cable
- Downward deflection in the front girders

Even though the partial UHPC deck showed an asymmetrical distribution of deflection in the whole structural system, the difference in deflections between the front and rear girders was not significant, as shown in Fig. 5. Figure 7 shows the cost analysis when materials at different levels of performance were employed in the bridge, indicating that the partial UHPC application had a highly competitive price.

Table 4. Deflection of Girders when Concrete at Different Levels of Performance was Applied.

	Short-term deflection (before considering creep and drying shrinkage)	Long-term deflection (after considering creep and drying shrinkage)
OPC application		
Partial UHPC application		
Full UHPC application		

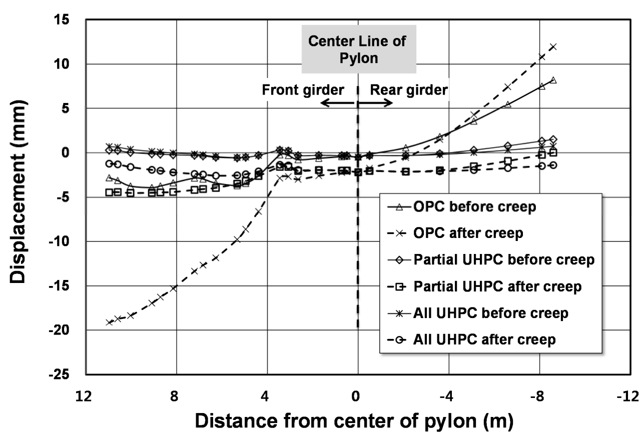


Fig. 5. Distribution of Deflection of the Girders.

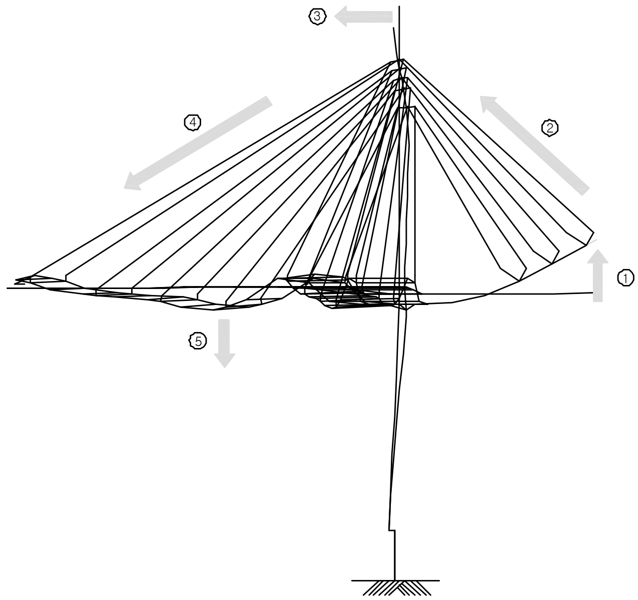


Fig. 6. Long-term Deflection due to Unbalanced Self-weight of Girders.

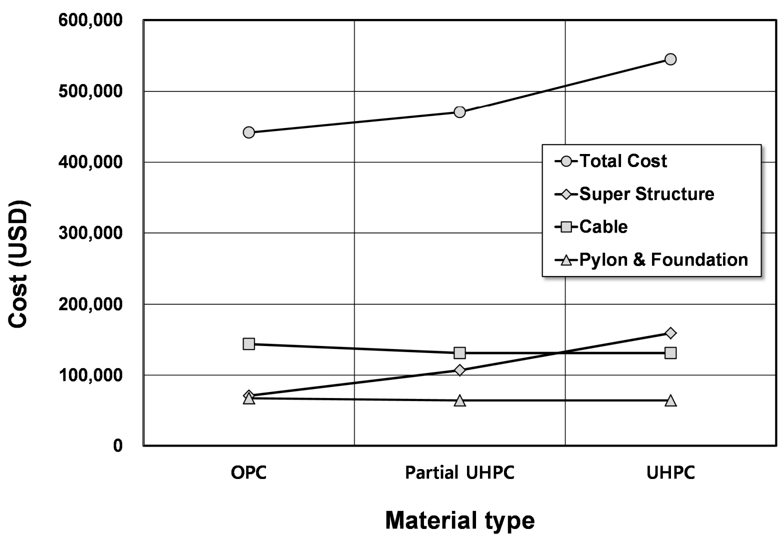


Fig. 7. Cost Analysis of UHPC.

3.4. Planning of pylon

The slope of the pylon with regard to the vertical line may occur in real-world construction projects. In order to investigate the constructability of the pylon, the slopes in the range of 0 to 4 degrees were considered as shown in Fig. 8 and the moment at the bottom of the pylon was calculated. Table 5 shows the calculated bending moment at the bottom of the pier with and without considering the time-dependent behavior. As the angle of the pylon decreased, the larger positive bending moments at the bottom developed.

Table 5. Bending Moment at the Bottom of the Pylon.

Bending Moment (kN.m)	0°	1°	2°	3°	4°
Before creep	-130.8	167.3	465.2	763.3	1061
After creep	-114.3	183.1	480.4	777.8	1075

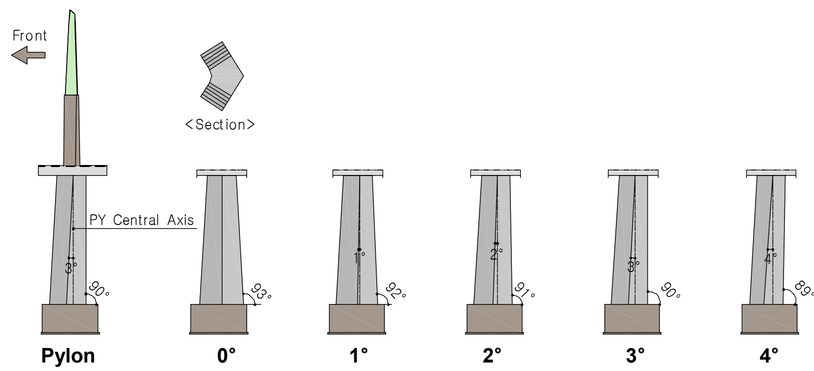


Fig. 8. Slopes of Pylon.

Less displacement developed at the top of the pylon as the angle was reduced. As shown in Fig. 9, slopes of three and four degrees both produced a desirable distribution of overall displacement in the pylon. However, the time-dependent behaviors might have caused rotation of the girder if a four-degree slope was employed. Therefore, the design ultimately employed a slope of three degrees.

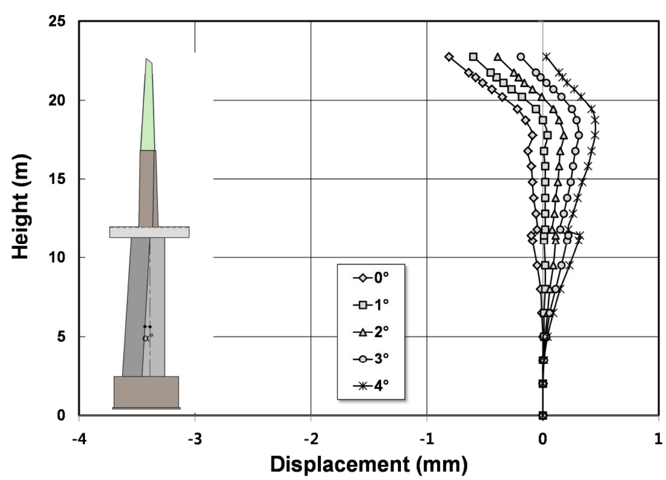


Fig. 9. Distribution of Displacement in the Pylon.

4. Conclusions

The pedestrian cable-stayed bridge with partial application of UHPC was designed and successfully constructed in South Korea. The ultra-high strength characteristics of UHPC reduced the thickness of the girders, thus decreasing the self-weight, and greatly benefiting the bridge's design. Both short-term and long-term deflections decreased when UHPC was employed in the bridge. Furthermore, the cost analysis indicates that UHPC offers a highly competitive cost compared to other materials. The economic advantage of UHPC application depends on the size and conditions of bridges. This study indicates that UHPC can be efficiently used in super-long span bridges.

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