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Conceptual Design of Hybrid Cable-Stayed Bridge with Central Span of 1000 m Using UHPC

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ABSTRACT

Ultra-high performance concrete (UHPC) is featured by a compressive strength 5 times higher than that of ordinary concrete and by a high durability owing to the control of the chloride penetration speed by its dense structure. The high strength characteristics of UHPC offer numerous advantages like the reduction of the quantities of cables and foundations by the design of a lightweight superstructure in the case of the long-span bridge preserving its structural performance through axial forces and structures governed by compression. This study conducted the conceptual design of a hybrid cable-stayed bridge with central span of 1000 m and exploiting 200 MPa-class UHPC. The economic efficiency of the conceptual design results of the hybrid cable-stayed bridge with central span of 1000 m and of Sutong Bridge, the longest cable-stayed bridge in the world, was analyzed.

Keywords: Ultra-High Performance Concrete; UHPC; Cable-Stayed Bridge; 200 MPa-Class; Sutong Bridge

1. Introduction

Reducing the weight is a priority for achieving economic construction of long-span bridges. This can be achieved by reducing the weight of concrete itself or by realizing lightweight cross section through the reduction of its dimensions using concrete with higher strength. In such aspect, ultra-high performance concrete (UHPC) is featured by a compressive strength 5 times higher than that of ordinary concrete and by a high durability owing to the control of the chloride penetration speed by its dense structure. Active and competitive R&Ds are being currently performed worldwide on UHPC. Advanced countries in the domain of bridge construction like Germany, Japan and USA have recognized the potential of UHPC as the material of the next generation and are today striving keen competition to monopolize the related technology, which already resulted in numerous successful outcomes and in the verification of its applicability through real constructions. A review of the constructions that exploited UHPC reveals numerous examples like the UHPC bridge with π-shape girder of the FHWA in USA. In Korea, there is the Seonyu pedestrian bridge completed in 2002 to commemorate the centenary of the Korea-France friendship relations but this bridge used imported UHPC of the French company Bouygues and its design and erection relied completely on French technologies. In order to face this worldwide trend, the Korea Institute of Construction Technology (KICT) implemented R&D on UHPC since 2002 and erected successfully a pedestrian cable-stayed bridge (**Figure 1**) using the fundamental technologies of the 200 MPa-class UHPC secured through the R&D [1-3].

The high strength characteristics of UHPC offer numerous advantages like the reduction of the quantities of cables and foundations by the design of a lightweight superstructure in the case of the long-span bridge preserving its structural performance through axial forces and structures governed by compression. Accordingly, this study conducts the conceptual design of a hybrid cable-stayed bridge with central span of 1000 m and exploiting UHPC (SuperBridge 1088). Moreover, the economic efficiency is analyzed through comparison with Sutong Bridge, the longest cable-stayed bridge in the world.

2. Sutong Bridge

Sutong Bridge is a bridge of 35.2 km composed of elevated viaducts on its northern and southern sides and the main bridge spanning the Yangtze River between Nantong and Changshu. Within the main bridge, the cable-

Figure 1. View of pedestrian cable-stayed bridge.

stayed bridge section bears 7 spans for a total length of 2088 m with a central span of 1088 m, making it the longest cable-stayed bridge in the world (**Figure 2**).

Sutong Bridge is a 6-lane highway bridge designed to last 100 years for vehicles running at 100 km/h. The cross section of the superstructure in **Figure 3** is equipped with wind noses at its extremities to provide an aerodynamically advantageous shape. The girder depth is 4 m and the sag is 16 m in the central span and 12 m in the side spans. The thickness of the top flange varies from 14 to 22 mm and the upper U-ribs with thickness of 8 to 10 mm are disposed at spacing of 600 mm. The thickness of the lower flange varies from 12 to 24 mm and the lower U-ribs with thickness of 6 to 8 mm are disposed at spacing of 800 mm. A thickness of 30 mm is applied for the web and diaphragms are installed every 4 m. The bridge is located in a seismic zone VI referring to the Chinese earthquake criteria. The design wind speed after completion is 38.9 m/s at height of 10 m with return period of 100 years. The maximum wind load is 25 m/s when combined with the live loads. The wind speed during construction was 35.4 m/s with return period of 30 years.

The inverted Y-shape pylons are made of concrete and rise at 306.4 m from the ground and 230.14 m from the top of the girder. The cross section of the leg at the top of the pylon is a tapered hollow section with dimensions varying from 9 m × 8 m to 10.8 m × 17.4 m and a thickness of 1.2 m. The central and bottom legs present tapered cross section with dimensions varying from 10.8 m × 6.5 m to 15 m × 18 m and thickness varying from 1.5 m to 1.8 m. The connection between the pylon and girder is achieved by means of nonlinear dampers. The nonlinear dampers allow displacement under ordinary conditions but resist to displacement under seismic event or gust. The pylons are designed to sustain the corresponding forces.

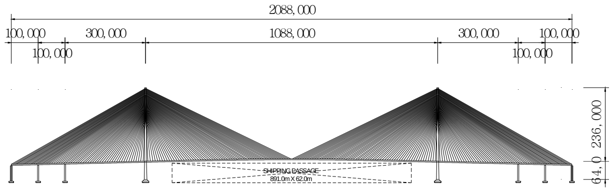


Figure 2. Sutong Bridge.

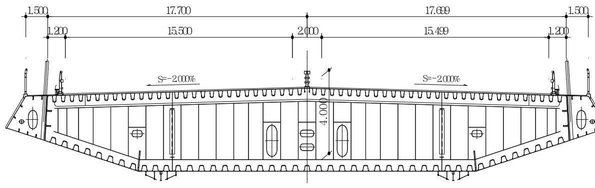


Figure 3. Stiffening girder of Sutong Bridge.

3. Conceptual Design of Hybrid Cable-Stayed Bridge with Central Span of 1000 m

3.1. Design of Cross Section

The stiffening girder determines not only the type of the whole structural system but also has also decisive effect on the size of the permanent loads and wind load. Moreover, the shape of the stiffening girder is also critical in terms of the aerodynamic stability. The selection of the cross section of the stiffening girder occupies thus a place of importance during the design process of the cable-stayed bridge. This study examines the feasibility of the edge girder and box girder as stiffening girder for the hybrid cable-stayed bridge with main span of 1000 m. The advantages and disadvantages of these two types of girder are arranged in **Table 1**. In general, the edge girder is known to be more advantageous than the box girder when the resistance to vibration caused by wind is primordial. Besides, the edge girder exhibits smaller torsional stiffness than the box girder but is lighter and offers higher economic efficiency. Following, the optimal cross section is selected after comparative analysis of the given conditions with respect to the advantages and disadvantages of each type of girder. In this study, the cables are assumed to be arranged in two planes for the edge girder and in one plane for the box girder considering the tension of the cables. The considered cross sectional shapes are illustrated in **Figures 4** and **5**. The cross sectional area and second moment of area are respectively 10.932 m^2 and 5.835 m^4 for the edge girder, and respectively 26.745 m^2 and 73.302 m^4 for the box girder. UHPC being a material specifically conceived to resist compressive stress exhibits small flexural rigidity but is very light. Consequently, it appears that the edge girder can be recommended as stiffening girder for the hybrid cable-stayed bridge.

Table 1. Comparison of edge girder and box girder.

Member	Edge girder	Box girder
Cable	Cables arranged in 2 planes—2 pylons Small amount of cable owing to light weight	Cables generally arranged in 1 plane (1 pylon) Large amount of cable due to heavy weight
Slab	Small effective width	Outstanding structural efficiency owing to large effective width
Stiffening girder	Weakness to flutter due to increase of mass moment of inertia Increase of deflection due to small stiffness of girder	Poor constructability due to increase of number of cells Remarkable torsional stiffness Small deflection owing to large stiffness of girder

3.2. Arrangement of Cables

The optimal cable-stayed bridge system is selected through analysis of the structure and the economic efficiency for two types of cable arrangement that are the fan type and harp type. In general, the harp type requires pylons with height approximately 25% higher than that of the fan type. The harp type necessitates thus longer length of the cables but offers satisfactory structural efficiency because of the larger angle of inclination of the cables at both sides of the pylon. However, the unavoidably smaller angle of inclination of the cables around the pylon may provoke interference with the vehicles when using the inverted Y-shape pylon. Therefore, the H-shape pylon is preferred but such choice increases the material quantities of the pylon. On the other hand, the lower height of the pylon in the fan type reduces relatively the effect of wind loading and increases the axial force transmitted to the pylon due to the smaller angle of inclination of the cables. Accordingly, the fan type appears to be appropriate for UHPC. The construction cost required per type of cable arrangement is arranged in **Table 2**. The construction cost discards the construction cost relative to the erection and is the sum of the construction costs of the upper girder, cables and pylons. The results show that the fan type is more economical than the harp type by about 10%.

The harp type presents generally lower structural efficiency of the cables than the fan type and necessitates higher pylons to achieve cable efficiency comparable to the fan type. In such case, longer cables are required and lead to the augmentation of the quantities. The need for pylons higher by 25% than those of the fan type results in longer construction period and increases the risk of buckling, which in turn may require excessive cross section at the bottom of the pylon. In addition, the bridge sites are often constrained to height limits.

Analysis showed that there is poor difference in the level of stress occurring in the girder according to the arrangement of the cables. This means that axial loads of similar level are introduced in the girder. The harp type provides remarkable stiffness of the girder which, under the application of the live loads, results in smaller deflections satisfying the allowable values. Since long-span cable-stayed bridges may require excessively high pylons, adverse effects may occur not only in terms of the attending construction constraints but also in terms of the structural safety. Even if both harp type and fan type can

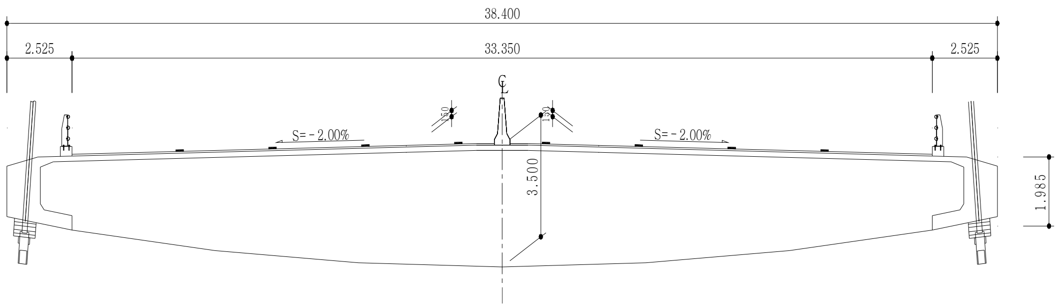


Figure 4. Edge girder.

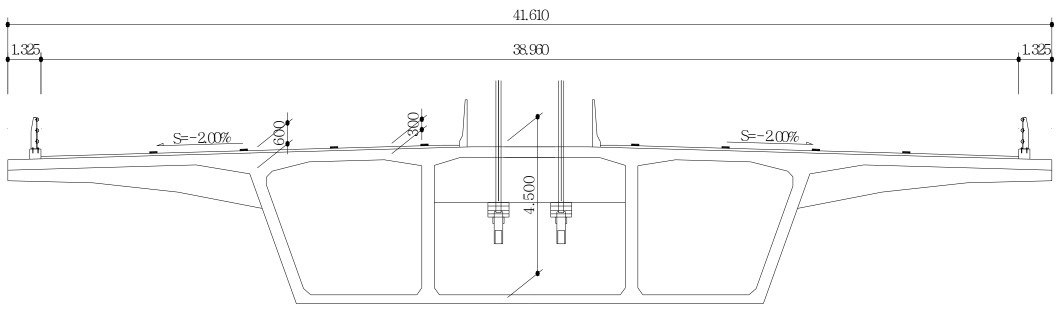


Figure 5. Box girder.

Table 2. Quantities and construction costs according to arrangement of cables.

Member	Fan	
	Quantity (ton)	Construction cost (10^6 KRW)
Girder	91,433	75,889
Cable	9798	99,935
Pylon	126,587	75,446
Total	-	251,270 (100%)
Member	Harp	
	Quantity (ton)	Construction cost (10^6 KRW)
Girder	91,433	75,889
Cable	10,105	103,074
Pylon	153,518	97,456
Total	-	276,420 (110%)

Table 3. Quantities and construction costs according to support type.

Member	Bearing	
	Quantity (ton)	Construction cost (10^6 KRW)
Girder	91,433	75,889
Cable	9798	99,935
Pylon	126,587	75,446
Total	-	251,270 (100%)
Member	Floating	
	Quantity (ton)	Construction cost (10^6 KRW)
Girder	90,814	75,375
Cable	10,038	102,392
Pylon	126,587 (w/o bearing)	75,246
Total	-	253,013 (101%)

be applied in case of short main span, the application of the fan type is recommended to satisfy the economic efficiency and structural safety for the cable-stayed bridge with main span of 1000 m considered in this study.

3.3. Support Type of Upper Girder

The support of the stiffening girder at the pylon of the cable-stayed bridge can be subdivided in three types: rigid link with the pylon, bearing support, and cable support. Even if large stresses are generally developed in the upper chord of the girder due to the large negative moments provoked by the live loads at the pylon of the cable-stayed bridge, this portion corresponds to the place with the maximum axial force in the cables. Accordingly, the compressive stresses in the lower chord are often more problematic than the stresses in the upper chord. In such case, the cross section of the support section is frequently enlarged excessively to control these compressive stresses. To overcome this problem, floating type girder is often adopted to avoid the installation of bearings to support the stiffening girder at the pylon. However, the floating type weakens the stiffness of the girder around the pylon, which may increase the risk of excessive vibration of the cables during a seismic event and renders it difficult to control the longitudinal displacement. The structure and economic efficiency are analyzed for two support types, the bearing type and floating type, in order to select the optimal cable-stayed bridge system. **Table 3** compares the construction costs according to the support type. The construction cost discards the construction cost relative to the erection and is the sum of the construction costs of the upper girder, cables and pylons. The comparison reveals that the bearing support is slightly more economical than the floating type but the difference remains smaller than 1%.

The floating type eliminates the occurrence of negative moments by removing the bearings at the pylon and is effective in controlling the tensile stress in the upper chord of the cross section. In cable-stayed bridges using ordinary concrete, the control of the stresses in the upper chord done through the axial force of the cables or through additional arrangement of tendons may result in compressive stresses exceeding the allowable stress. However, the bridge considered in this study uses UHPC and is featured by an allowable compressive stress at least 6 times larger than ordinary concrete. Therefore, the pylon is capable of supporting the compressive stress without problem. In addition, the floating type necessitates the installation of dampers to mitigate vibrations around the pylon. Accordingly, the application of the bearing support type is recommended for the cable-stayed bridge under concern owing to its large vertical and torsional stiffness.

3.4. Comparison According to Girder Stiffness

The main factors determining the overall stiffness of the cable-stayed bridge are the stiffness of the stiffening girder, the diameter and number of cables, and the stiffness of the pylon. Among them, the stiffness of the stiffening girder is of particular importance for the overall stiffness since it has direct effect not only on the stresses occurring in the girder but also on the deflection caused by the live loads. However, larger stiffness means larger cross sectional area of the stiffening girder and results in the increase of the quantities of cables. The effect of the depth of the girder on the whole system and economic efficiency is analyzed for two depths of 1.735 m and 2.1 m. **Figures 6** and **7** present the standard cross section of

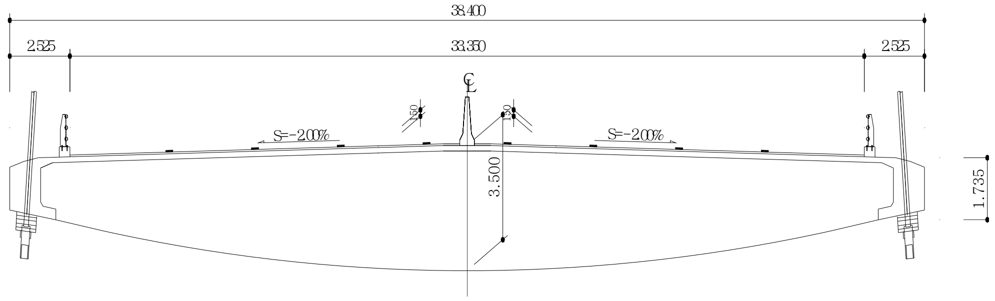


Figure 6. Standard cross section, H = 1.735 m.

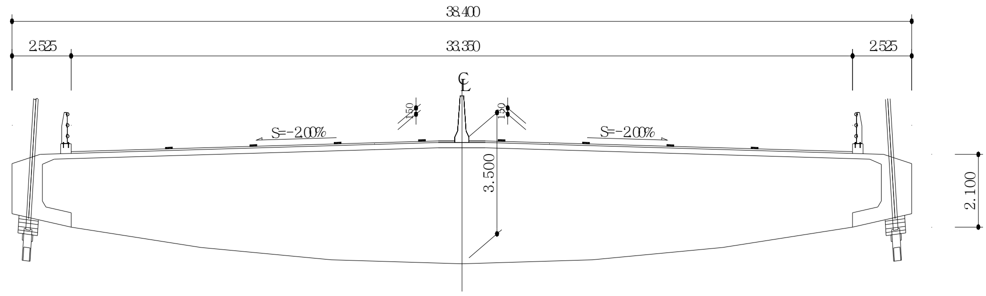


Figure 7. Standard cross section, H = 2.1 m.

the stiffening girder for girder depth of 1.735 m and 2.1 m, respectively.

Table 4 compares the construction costs according to the stiffness of the girder. In view of the construction costs only, it seems that smaller girder depth is more economical but the arrangement of tendons to resist the tensile stresses at mid-span is not only difficult but also causes problems in the stability of the anchorages of the tendons.

Reducing the depth of the girder favors the reduction of the amount of cables and reduction of the girder weight. However, reducing the height of the cross beams (3.5 m) appears to be impossible in the case of wide cross section in the lateral direction and leads to inharmonious cross sectional shape at the whole. The precast bridge shall be conceived so that tensile stresses do not occur in the connection. This can be advantageously realized by the adoption of large girder depth. Moreover, the adoption of large girder depth enables to reduce the need for steel bars during the erection, which provides outstanding constructability. Consequently, it appears that the appropriate depth of the stiffening girder is 2.1 m.

Table 4. Quantities and construction costs according to stiffness of girder.

Member	H = 2.1 m	
	Quantity (ton)	Construction cost (10^6 KRW)
Girder	91,433	75,889
Cable	9798	99,935
Pylon	126,587	75,446
Tendon	359	3,533
Total	-	254,803 (100%)
Member	H = 1.735 m	
	Quantity (ton)	Construction cost (10^6 KRW)
Girder	83,350	69,181
Cable	9321	95,073
Pylon	126,587	75,446
Tendon	932	9176
Total	-	248,876 (97.7%)

4. Comparison of Economic Efficiency

Figure 8 presents the standard cross section resulting from the conceptual design of the hybrid cable-stayed bridge with central span of 1088 m. **Table 5** compares the material quantities of the SuperBridge 1088 and Sutong Bridge. PWS cables are applied with 139 to 313 strands for Sutong Bridge and 61 to 397 strands for SuperBridge 1088. The analysis of the economic efficiency of SuperBridge 1088 and Sutong Bridge in **Table 6** shows that the construction cost relative to the material quantities of the hybrid cable-stayed bridge designed in this study reaches 85.3% of that of Sutong Bridge and verifies that the hybrid cable-stayed bridge secures sufficient economic efficiency. In view of the cost ratio per detailed process, the superstructure of Sutong Bridge appears to contribute mostly to the construction cost (**Table 7**). For SuperBridge 1088, the contribution of the cables to the construction cost is larger than that of the

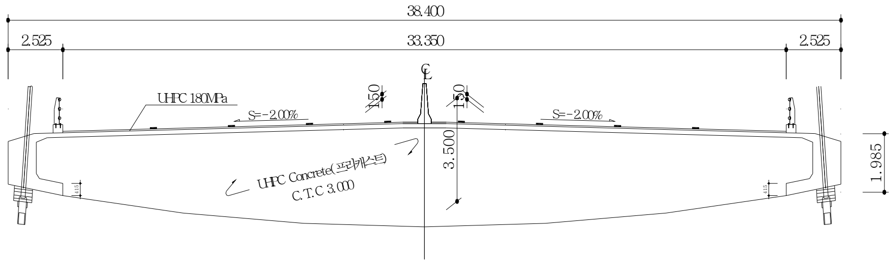


Figure 8. Conceptually designed standard cross section.

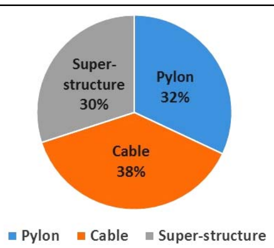
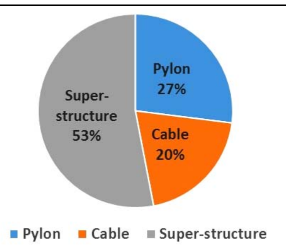
Table 5. Bill of quantities (ton).

Member		SuperBridge 1088	Suton Bridge
Super-structure	Steel	-	48,800.0
	UHPC	116,540.0	-
	Steel wire	1,176.4	-
	Steel bar	31.6	
Cable		10,550.0	6,260.0
Pylon		133,250.0	133,250.0

Table 6. Comparison of construction costs (direct costs, 10^6 KRW).

Member		SuperBridge 1088	Sutong Bridge	Difference ratio
Super-structure	Steel	-	186,463	−52.6%
	UHPC	73,206	-	
	Steel wire	9930	-	
	Steel bar	5225	-	
Cable		116,376	69,690	67.0%
Pylon		94,263	94,263	0.0%
Total		299,000	350,416	−14.7%

Table 7. Comparison of construction costs per work process.

SuperBridge 1088	Sutong Bridge
	

superstructure but this result is due to the absence of the erection cost in the comparison.

5. Conclusion

This study conducted the conceptual design of a hybrid cable-stayed bridge with central span of 1000 m and exploiting 200 MPa-class UHPC. The edge girder and box girder were compared to select the appropriate stiffening girder. The application of the fan type for the arrangement of the cables was chosen considering the structural stability and economic efficiency. The comparison of the bearing type and floating type as support type revealed that the difference in the construction cost remained below 1%. The floating type was seen to necessitate the installation of dampers to mitigate the vibrations around the pylons. Therefore, the bearing support was selected for the cable-stayed bridge with central span of 1000 m owing to its large vertical stiffness and torsional stiffness. Two girder depths of 1.735 m and 2.1 m were examined. The smaller girder depth appeared to be economically efficient in terms of the construction cost. However, reducing the height of the cross beams (3.5 m) was seen to be impossible in the case of wide cross section in the lateral direction leading to inharmonious cross sectional shape at the whole. The girder depth of 2.1 m was thus selected. The economic efficiency of the conceptual design results of the hybrid cable-stayed bridge with central span of 1000 m and of Sutong Bridge, the longest cable-stayed bridge in the world, was analyzed. The comparison showed that the construction cost relative to the material quantities of the hybrid cable-stayed bridge designed in this study reached 85.3% of that of Sutong Bridge and verified that the hybrid cable-stayed bridge secures sufficient economic efficiency.

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