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Christian Menn's recent bridge designs – Reducing structural elements to the simplest solution

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Summary

The conceptual designs by Christian Menn of four landmark bridges are presented: 1) a 350-m span cable-stayed bridge with jointless deck girder, 2) a cable-stayed bridge with a single “spindle-shaped” pylon, 3) a bridge with an arch reaching high above the deck (both carrying a horizontally curved deck girder), and 4) a cable stayed bridge with three pylons monolithically connected to the deck girder. All of the original bridge designs are driven by the aim to optimize the flow of forces with the objective to reduce structural elements and their dimensions to a minimum.

The four bridges express technical efficiency by slenderness and transparency and emphasize the importance of understanding the functioning of the structural systems. A sound engineering concept is thus the solid basis for a far-reaching aesthetic quality and for the conceptual design of simple but elegant structures that offer a great crossing experience while respecting the functional requirements and providing technical performance.



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ABSTRACT: The conceptual designs by Christian Menn of four landmark bridges are presented: 1) a 350-m span cable-stayed bridge with jointless deck girder, 2) a cable-stayed bridge with a single “spindle-shaped” pylon, 3) a bridge with an arch reaching high above the deck (both carrying a horizontally curved deck girder), and 4) a cable stayed bridge with three pylons monolithically connected to the deck girder. All of the original bridge designs are driven by the aim to optimize the flow of forces with the objective to reduce structural elements and their dimensions to a minimum.

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1 INTRODUCTION

The art of bridge design consists in balancing economy and aesthetics against each other on a case by case basis to achieve the desired design objectives. Functional requirements comprising among others traffic loads and clearances, topography and geology, and consideration of state-of-the-art technologies need to be satisfied. The resulting bridge designs must be compatible with the environment and visually pleasing as an entity [Menn 1996, Menn 1998].

Albert Einstein's dictum stating that “Everything should be made as simple as possible, but not simpler” also applies to the technical-functional domain. In bridge design, reducing structural elements to the simplest solution is always a meaningful approach that often leads to original structural shapes with an aesthetic quality determined by natural science.

Following this approach, the conceptual designs for the upcoming construction of four landmark bridges are presented: a 350-m span cable-stayed bridge with jointless deck girder, a cable-stayed bridge with a single “spindle-shaped” pylon, a bridge with an arch reaching high above the deck (the last two carrying a horizontally curved deck girder), and a cable stayed bridge with three pylons monolithically connected to the deck girder.

The technical efficiency of all of these bridge designs is achieved by optimizing the flow of forces with the objective to reduce structural elements and their dimensions to a minimum. A sound understanding of the technical functioning of the structural systems with respect to the functional requirements is central. The result of this engineering design process are esthetically pleasing structures characterized by their bold slenderness and transparency.

2 CABLE-STAYED BRIDGE OVER THE LAKE OF GRIMSEL, SWITZERLAND

Plans to raise the Grimsel dam and lake require redrawing of the road over the Grimsel Pass. Close to the Grimsel Hospiz, the road has to cross more than 300 m across the artificial lake. Preliminary studies showed that it is advantageous to bridge the lake in one leap.

In 2005, Christian Menn designed a cable-stayed bridge crossing the lake with a single span of 352 m supported by two vertical 75-m high inversed Y-shaped pylons (Fig. 1). The slender deck slab with a total width of 10.9 m and a thickness of 1.2 m is carried by two slightly inclined planes of stay cables that are fixed at the deck edges and provide torsional stiffness to the deck. The two planes of stay cables are fixed along the pylon needle and are bundled in one plane and back-anchored to the nearby rock.

The aesthetic expression of the bridge is characterized by the slender deck and pylons having a simple and pure shape as well as the semi-fan arrangement of the stay cables and their concrete anchorage blocks shaped like mountain crystals. This bridge structure is the result of a design process reducing structural elements to meet the given functional and environmental requirements.

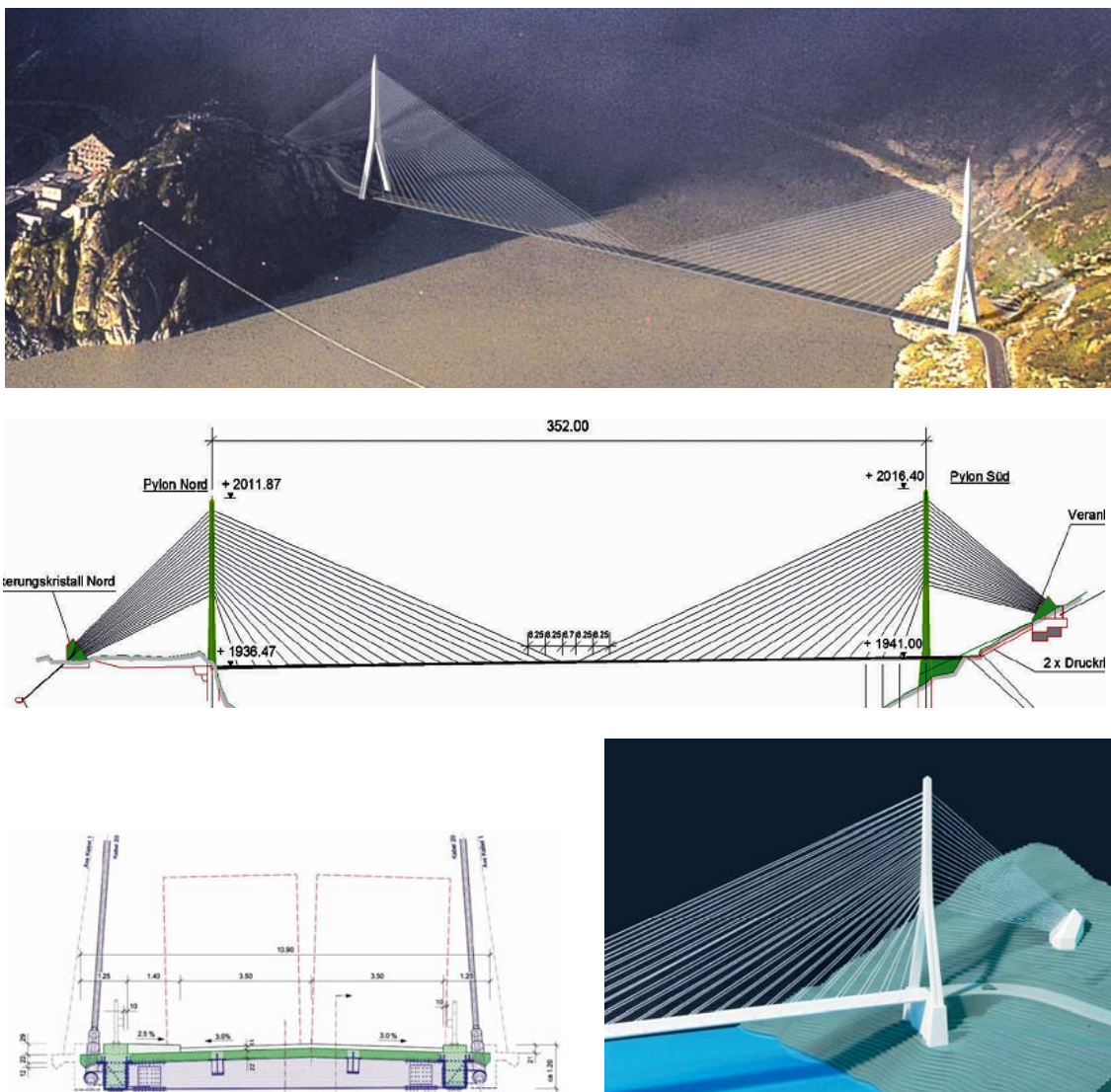


Figure 1: Cable-stayed bridge over the artificial lake of Grimsel

Exposure to severe environmental conditions at 2'000 m altitude in the Swiss Alps necessitated the detailed investigation of three major environmental actions on the structure:

Wind speed measurements from the weather station at the nearby Grimsel Hospiz were available. These measurements were translated to the specific conditions of the bridge site which is somewhat protected from the wind in a valley-like location below the weather station. The measurements revealed that the governing wind action is in the north-south direction almost along the bridge axis and the wind action in the east-west direction perpendicular to the bridge is relatively small. A maximum wind speed of 57 m/s was considered that lead to the design wind force of about 2kN/m^2 (with 50 year return period) in the north-south direction. The cross section of the deck girder was developed based on aerodynamic investigations. Although the wind action perpendicular to the deck is relatively modest, studies of the aerodynamic behavior of the deck revealed that a “nose”-detail along the edges of the deck results in significant wind stability of the deck. Furthermore, the initially designed tapering of the deck width approaching the abutments has been proven not to be necessary for resisting the lateral moments, thus leading to a further simplification of the structure.

The deck slab is a composite steel-concrete construction rigidly fixed to the abutments located at the base of the pylons. It will be built from each pylon in segmental sequence to the mid-span where the two deck halves will be rigidly connected without a joint. In fact, the structural analysis revealed that the initially designed hinge at the mid-span is not necessary as the dilation of the jointless deck subjected a temperature variation between -20°C and $+30^{\circ}\text{C}$ is resisted by the structure. However, in order to limit built-in stresses in the restrained deck, the temperature at the time of connecting the two deck halves must be about 5°C .

The third environmental action to consider concerns the formation of ice on the stay cables when freezing rain accumulates on them to form icicles. However, this phenomenon is not significant since such icicles drop off due to their dead weight. Another phenomenon leading to an ice crust on the stay cables occurs when, at temperatures ranging from 0°C to -10°C , under-cooled fog flows in laminar flow around the stay cables. In analogy with observed ice formation on high-voltage power lines, an ice thickness of 10 cm (corresponding to an additional load of 0.5 kN/m on the cables) is considered in the design.

Considering all these actions on the structure, the maximum vertical deflection of the optimized deck under design traffic load as the governing action was calculated to be $1/450$ of the span, while the maximum horizontal deflection due to wind as the governing action is $1/400$ of the span.

Being part of a major hydroelectric renewal project in the Grimsel area that is in the process of getting concession, the bridge project is awaiting its construction.

3 CABLE-STAYED BRIDGE IN ABU DHABI, UNITED ARAB EMIRATES

The Al-Sowah Island project in Abu Dhabi will comprise the Abu Dhabi Financial Centre, low density housing units and several high-rise buildings providing among others offices and retail areas. A three lane carriageway in each direction will link the offshore island to the main land. The roadway is curved with a radius of $1'000\text{ m}$.

The design developed by Christian Menn in 2008 is a proposed cable-stayed structure with a single 118 m high pylon between two main spans of 205 m, bridging the waterway (Fig. 2). The major design challenge is due to the curvature of the deck slab leading to significant torsional moments to be resisted by the structure.

The cable-stayed structure is characterized by the “spindle-type” pylon and a fan-shaped cable arrangement in one plane that follows the roadway curvature in the middle of the deck. Menn developed the spindle pylon when studying the optimal solution for cable-stayed bridges with very large decks in retrospect of his design of the Leonard Zakim Bunker Hill Bridge built in 2002 in Boston. The spindle pylon is composed of a needle for cable fixation and a bracing system which provides the high lateral resistance of the pylon to bending forces due to eccentric live load or horizontal curvature of the roadway deck. This enables in return a simple and slender cross section for the roadway deck, thus avoiding complicated and heavy box cross sections that are often necessary for cable-stayed bridges with central pylons.

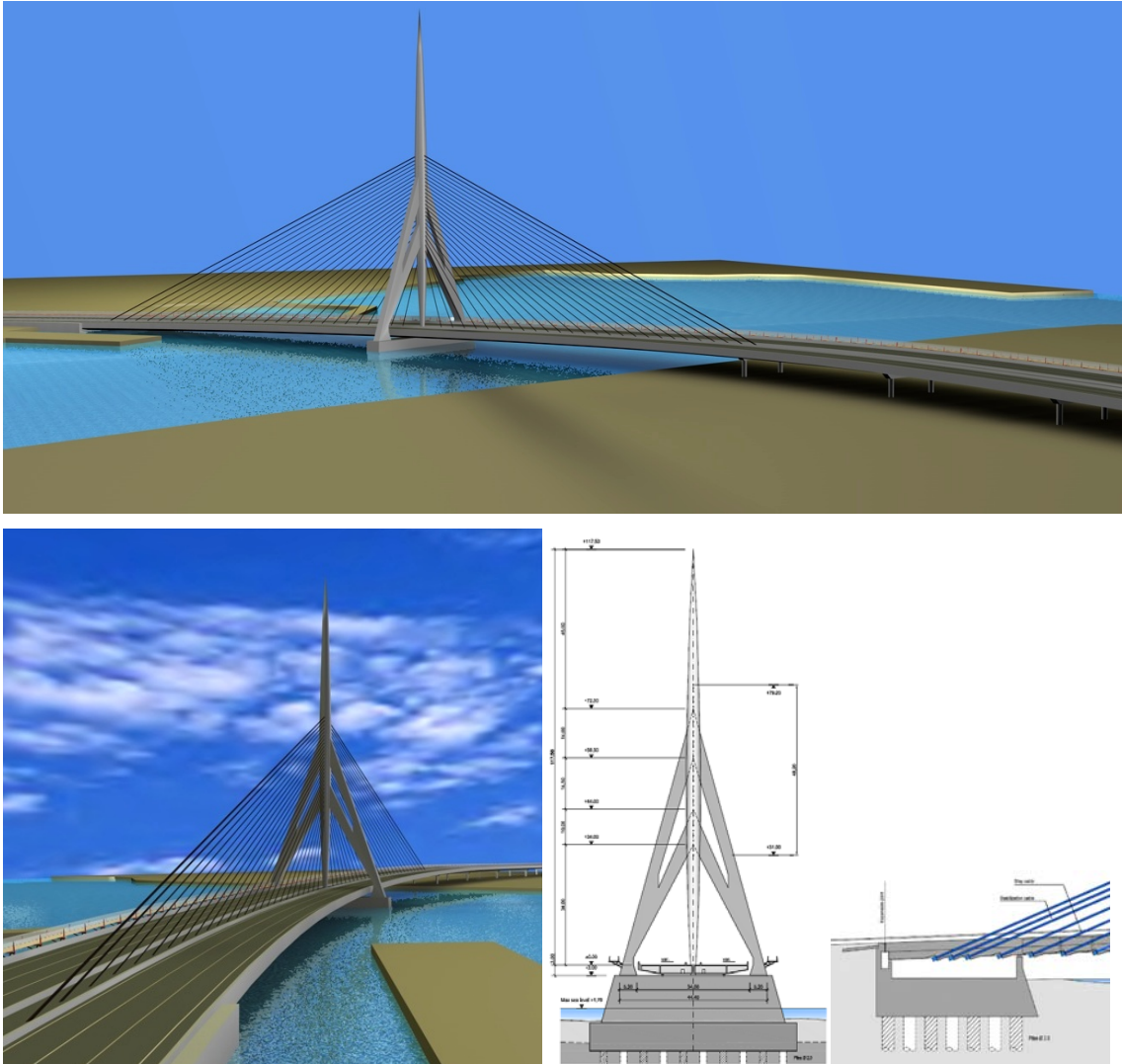


Figure 2: Cable-stayed bridge with curved deck in Abu Dhabi.

The curved deck slab with a thickness of only 2.6 m is suspended from the pylon by one plane of stay cables. Since the stay cables fixed along the curved centerline of the girder transmit their force from their slab fixation along a straight line to the tower needle, significant deviation forces result (in particular from the longer stay cables with the largest eccentricity from the bridge axis) that act in the lateral direction to the pylon. The important lateral bending of the pylon is resisted by the chosen spindle form whose strong double-arm bracing provides the necessary lateral stiffness. Thus, the torsional moment due to the permanent loads (dead loads) of the curved deck is taken by the pylon's lateral resistance. The structural system is balanced for permanent loads and only small bending moments due to vertical and horizontal forces appear in the deck. Essentially only the (circular) torsion due to an asymmetric alignment of traffic load needs to be carried by the deck, thus allowing for relatively slender box cross section.

The first bearings adjacent to the cable-stayed spans, i.e. at the abutment and first pier respectively on each side of the bridge, are of utmost importance. On the one hand, the cable stayed system is stabilized and stiffened in the longitudinal direction by the top three stay cables that are anchored beyond the first deck bearings (Fig. 2, bottom right). On the other hand, the horizontal bending moment in the deck due to the cable eccentricity with respect to the bridge axis is resisted by the rigid connection of the deck at these first bearings.

The bridge is in its final stage of design waiting for its construction in the near future.

4 ARCH BRIDGE IN ABU DHABI, UNITED ARAB EMIRATES

This bridge is part of a roadway extension to the Al-Sowah Island in Abu Dhabi. The roadway in the case of this bridge is curved with a radius of 900 m. The adoption of the curved deck is the result of a practical requirement and aesthetic considerations. The bridge carries a three lane roadway and a lightweight railway in each direction leading to an overall girder width of 42.1 m (including a central zone of 4.0 m for the arch and the vertical cable plane. In addition, a pedestrian lane of 2.5 m width is attached laterally on one of the inner edges of the curved deck.

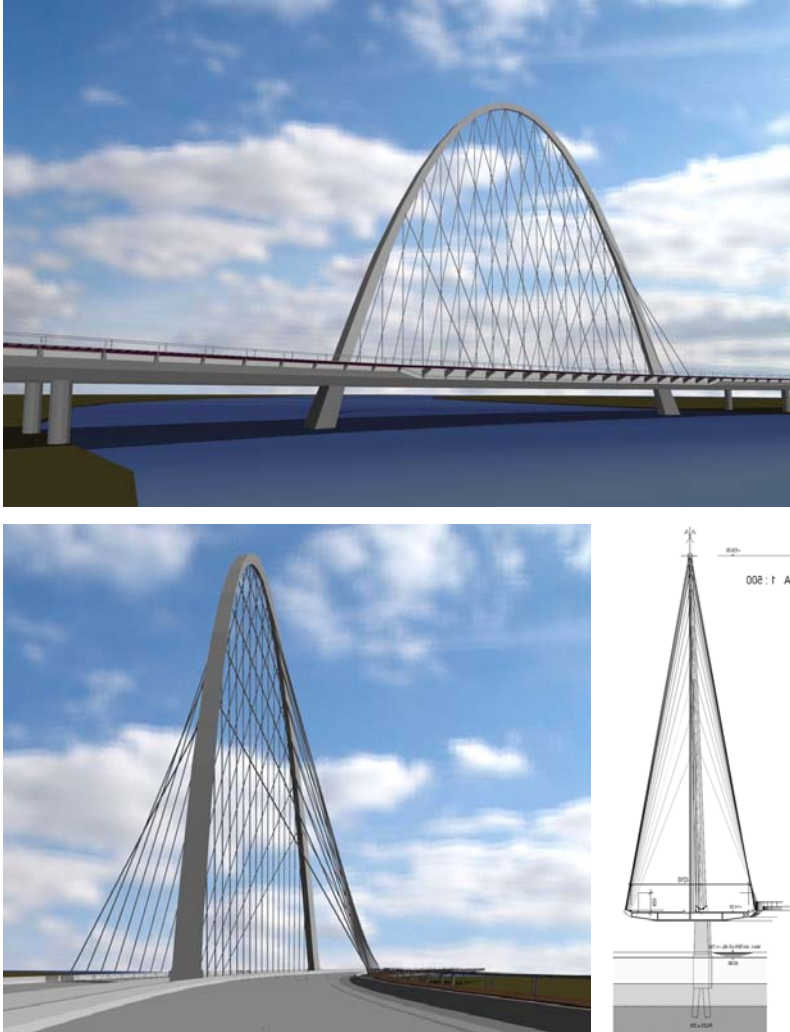


Figure 3: Arch bridge with curved deck in Abu Dhabi.

The main design challenge was again the curved deck. Menn developed a structural system consisting of a 117 m high steel arch for a deck span of 170 m (Fig. 3). The structure's main feature is this rather high arch with respect to the span which shall offer a great crossing experience and make this bridge a showpiece object. In addition, the aesthetic expression of the arch will be enhanced by a zinc-titanium cladding glittering in the sun.

The arch shape follows the girder axis and thus a spatial curve, i.e. the arch is always tangential to the girder axis. As a consequence, the resultant arch force is eccentric with respect to the arch base at the abutments that leads to significant out-of-plane second order effects.

The torsional moment due to the permanent loads (dead loads) of the curved deck is taken by the two inclined outer cable planes and the deck is suspended from the arch in the middle by a vertical cable plane. The difference in the forces between the outer cable planes is counteracting this torsional moment. In addition, the outer cable planes stabilize the arch. In this way, the

structural system is balanced for permanent loads. In order to optimize this balancing, some ballast (concrete) is further added to the inner edge zone of the deck.

Bending and torsional moments are resisted by the cross section of the box girder deck which is rigidly fixed to the short and thus stiff stub-like piers in the prolongation of the arch. The torsional moment due to asymmetric traffic load is resisted by the box section while the asymmetric traffic load along the bridge axis is carried by the deck's bending resistance and the stiff piers forming the arch abutments.

Overall, the present structural system can be seen as a new generation of the well-known deck-stiffened arch bridges developed by Robert Maillart. Vertical loads are suspended from the arch by means of the cables, while the arch transfers torsional and bending moments to the deck girder which itself is rigidly fixed to the stiff piers.

Similar to the previous bridge, the project is in its final design stage waiting for its construction to begin in the near future.

5 PEACE BRIDGE OVER THE NIAGARA RIVER, BUFFALO, USA

The existing beautiful multi-span steel-arch bridge built in 1927 over the 700 m wide Niagara River between Buffalo (USA) and Fort Erie (Canada) needs to be expanded to accommodate for future traffic needs. Contacted by the Peace Bridge Authority, Christian Menn developed between 2001 and 2006 several cable stayed designs for a “signature” bridge. Bridge design competitions were held and finally in 2006 Menn's design of a cable-stayed bridge with two spindle-pylons and a slender roadway deck with a main span of 500 m, aligned parallel to the existing bridge was selected for construction (Fig. 4).

However, environmental considerations resulted in a strong recommendation to drop the bridge design with 173-m (567-ft.) high pylons. In fact, a review has determined that the height of the two pylons would have unacceptable impact on migratory birds, and it was requested to review the design in favor of a lower profile bridge. Furthermore, it was decided that the new bridge shall replace the existing one.



Figure 4: Peace Bridge – Companion bridge design.

To meet these new requirements, in 2008 and 2009 in collaboration with Linda Figg from the Figg Engineering Group, Menn developed a structural system comprising a three pylon cable-stayed bridge structure with a harp shaped stay cable arrangement to carry a roadway with a total width of 20 m (65 ft.) (Fig. 5). The pylons with two needles vary in height, the highest being 72-m (236-ft.) high, for spans of 114 m (374 ft.) – 245 m (805 ft.) – 268 m (880 ft.) – 137 m (450 ft.). The highest tip of the structure is 84 m (276 ft.) above the water level.

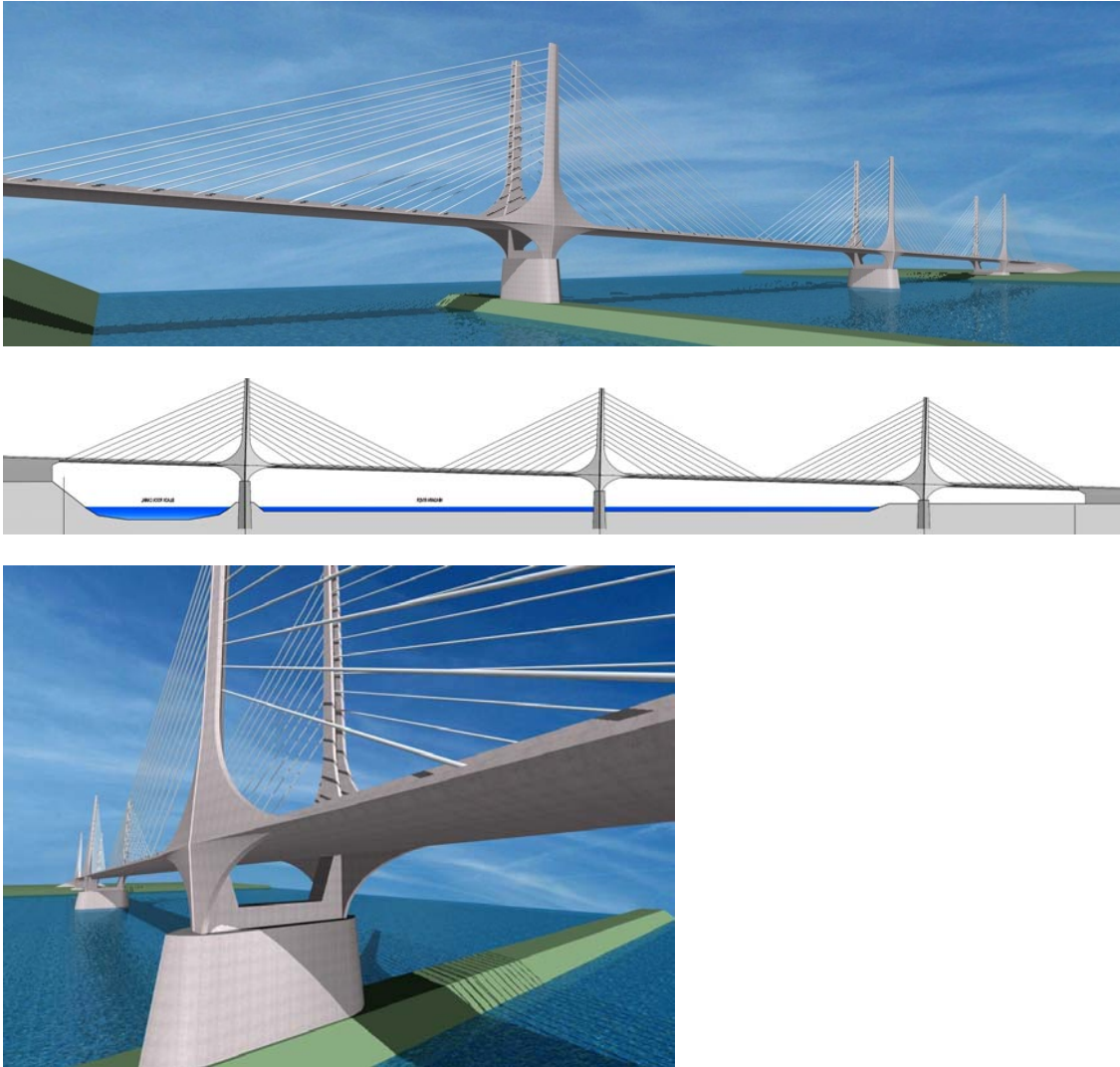


Figure 5: Peace Bridge – most recent design for a replacement bridge.

The main idea of the design is to provide three stiff triangular cable-stayed structures with the pylon and the deck girder forming a rigid node. The top cables transmit significant forces from the deck to the abutments where the deck girder has to be fixed. These main cables are anchored to the deck almost next to each other, such to avoid high stress concentration in the deck at mid-span due to differential cable forces.

The problem of stabilizing a cable-stayed structure with several spans in the longitudinal direction had to be addressed. Rather than linking the adjacent pylon tips by a horizontal cable or cross bracing two neighboring pylons, stabilization may also be obtained by a series of rigid pylon-to-deck girder systems. This is an efficient solution for bridges with rather short pylons and relatively short overall length such as the one in the present case.

The “nose-like” detail added to each edge of the deck improves the aerodynamic behavior of the structure and also emphasizes the deck girder slenderness and the rigid cross formed by the pylon and the deck.

The final bridge design is now with the Figg Engineering Group. The decision to begin construction in 2010 has not yet been taken.

6 CONCLUSIONS

The four presented designs of landmark bridges express technical efficiency with their accent on slenderness and transparency. They emphasize the importance of understanding how the structural systems function.

A sound engineering concept is the solid basis for a far-reaching aesthetic quality and for finding simple yet elegant structures offering a great crossing experience while respecting the functional requirements and providing technical performance. Guided by the basics of mechanics and natural sciences, this approach continues to be very efficient and valuable, in particular nowadays, when architect-led bridge designs (often based on a metaphoric idea) have produced structures that are excessively expensive to build and maintain.

The presented bridge designs are the result of the exclusive engagement of Christian Menn in bridge engineering. They result from his more than 50 years of continuous experimentation in the conceptual structural and aesthetic design of bridges.

This paper shows that bridge design is founded on creativity. The art of structural engineering is characterized by innovation and imagination with the objective to improve the environment through structural art.

The art of structural engineering should be appreciated again and be given much more importance in the education of structural engineers.

ACKNOWLEDGMENTS

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The detailed designs of the four bridge structures are performed by the ChristianMennPartners AG consisting of Christian Menn and three Swiss engineering companies (and their principal engineers), namely, Bänziger Partner AG (Dr. Werner Brändli), Dr. Deuring + Oehninger AG (Dr. Martin Deuring) and Walt + Galmarini AG (Carlo Galmarini). The author acknowledges their contribution to this paper in providing drawings, computer animations and detailed design information.

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