Phoenix taking off at Comacchio

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Summary

The Ferrara waterway, connecting this historic town with *Comacchio* on the Adriatic Sea is being upgraded: section widening and straightening as well as higher clearance has called for the replacement of most of the existing bridges. When approaching *Final di Rero* the waterway needs to be bifurcated to straighten a sharp bend leaving a dumpling shaped island between the new navigational channel and the existing one to be used as a mooring stretch. The new bridge fall just on the upstream vertex of this island, calling for two spans of 40 and 80 metres circa. The situation was clearly suited for a bow string solution. The proposed design, by inclining the hangers yields an asymmetric funicular of the two arches that while retaining structural efficiency gift the structure with the distinguished look of a wide winged bird at take off. Since the symbol of the *Comacchio's* fauna are the beautiful *Cenerino* herons stretching their slender wings across the water, the design was awarded and construction soon to take off.

Keywords: Bow string bridges, inclined hangers, asymmetric funicular, steel design .

1. Introduction

In the constant pursuit of innovation and citation, bridge design has tried to catch up with the contortions of modern architecture. Unfortunately, bridge design cannot disregard the law of gravity as much as buildings because trucks and trains are heavier than people and bending moment caused by spanning are more severe than those caused by warping the shape of a building. Having said that, perfect verticality and symmetry is not necessarily so advantageous as it may seems, because external actions do not always follow the same symmetry and verticality as the force of gravity does.

Arch bridges are particularly suited to manipulation because of their intrinsic redundancy and their aesthetic appeal. For small bridge span, say less than 150 m circa, the designer has maximum flexibility in the overall geometry and section type because forces are small and can be resisted even by fancy configurations, especially when arches and deck are made of steel. Consequently, arches have been rotated in all different positions, their shape distorted and all other sorts of eye catching manipulation have been tried up to the complete loss of their load bearing capacity leaving them only with an aesthetic function.

In any case, for spans up to 150m, bow strings are definitely more expensive then continuous girders and the same hold true for larger spans, where cable supported structures tends to be more economic. In the small span range though, tied arches can be sort of cost competitive if the design is reasonably simple and opens steel sections are used (plated girders). The obvious condition for keeping the costs within acceptable limits is that the arches geometry adhere to the load funicular so that bending moments under self weight are negligible.

Hanger configuration can also make a difference, especially for medium to large spans where the network layout [1] does reduce the bending moment in the arch and deck due to unsymmetric traffic loading. The exact quantification of the savings due to the network configuration is not straightforward though since this hanger arrangement does requires an higher number of these elements with more complicated anchorages compared to the standard (parallel) layout. For small spans where local effects are predominant, the network configuration may not provide significant advantages compared to the standard one.

When the authors were asked to put forward an alternative design for the twin bow string at *Final di Rero*, they felt it was the right occasion to finally implement their research on unsymmetric funicular. By inclining the hangers the arch funicular morphs into a very appealing wing profile that is only marginally less efficient than the symmetric configuration. By doing this the twin arches would recall the profile of a bird with spread wings. Since the bridge is located in an area (the *Comacchio* plain) famous for its *Cinerino* heron the choice was made.

Fig. 1: The bridge concept

2. The structural behaviour

In order to investigate the effect of inclining the hangers, we compared the behavior of the larger Phoenix arch with a symmetric one with the same span, height, self weight and member dimensions. Two finite element models have been set up with spans of 74 m, heights of 16.5 m and self weight of 6.5 ton/m. The two models are 2D with the 2 steel arches and deck lateral beams (ties) added onto a single plane. Member dimension and material properties are not particularly relevant to the comparison; the actual dimension and materials of the Phoenix bridge, as detailed in the following chapters, have been used for both models.

Since both arches follows the load funicular, bending moments in the arches and in the deck are negligible except for local effects. Axial forces in the two configurations do differ instead with the unsymmetric configuration showing a linearly increasing axial force in both arches and deck due to the horizontal component of the hangers pull. Vertical component in all hangers is equal to the deck self weight times the hanger spacing. Tensile force in the inclined hangers of the unsymmetric configuration is therefore greater than that of the symmetric one by a factor of $1/\cos(\alpha)$, with α being the inclination of the hangers that in this example and in Phoenix is 30 degrees to the vertical.

As one can see from Fig. 2, the average values of the unsymmetric configuration are very close to those found for the symmetric one. The two structures do require therefore the same amount of material except for the hangers of the unsymmetric configuration that need to have a larger section.

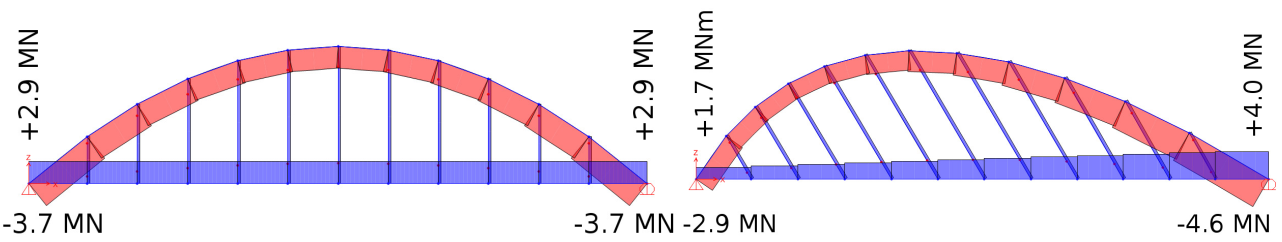

Fig. 2: Axial force distribution under self weight

Let us know see what is the behaviour of the two structures under live load. The standard Eurocode live loading made of a distributed load of 4.3 ton/m and a concentrated one of 10 ton/m over a 12 m length has been applied on the two structures. The bending moment envelops for the two structures show once again that the average values found for the unsymmetric configuration are very similar to those found for the symmetric one. In the unsymmetric configuration sagging moments are higher where the hangers are perpendicular to the arches that is where the curvature is higher and the axial force smaller.

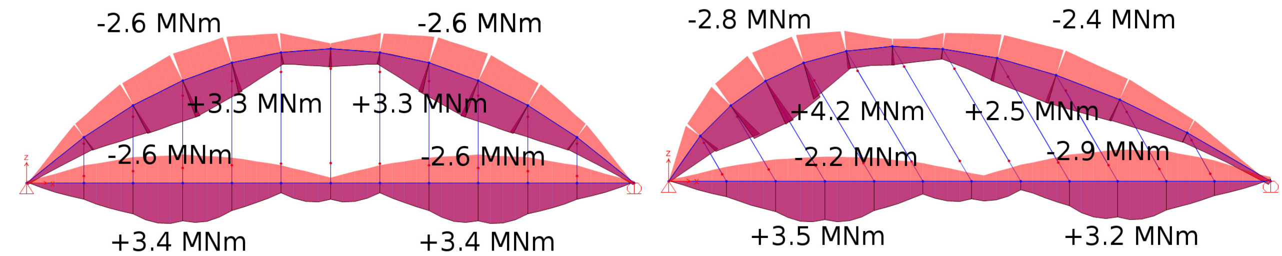

Fig. 3: Bending moments envelops due to live loading

The behaviour under live loading is confirmed when comparing the envelope of the deck deflection of the two structures. Once again, the unsymmetric arch is more efficient where the angle of incidence of the hangers to the arch is smaller with the average deflections of this configuration being very close to those found for the symmetric one.

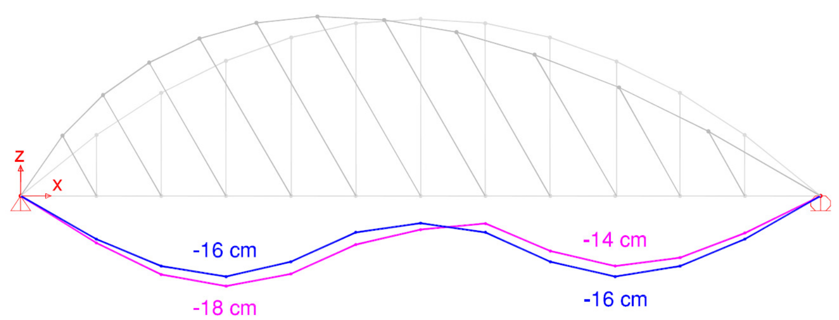

Fig. 4: Deck deflection envelops due to live loading

In conclusion, inclining the hangers does not seem to cause a significant loss of efficiency in the tied arch behaviour. This may not be valid for higher angles of hangers inclination or completely different ratio of arch to deck stiffness and therefore the proposed comparison do not pretend to be exhaustive of all possible configurations. Certainly, within the investigated range, the loss of efficiency is almost negligible especially when compared to other variations of the classical bow string configuration that are being proposed and built worldwide. Reference is made in particularly to the arch plane inclination that has a strong influence on the cross bracing and buckling response of the arches. We see today many tied arches that for aesthetic reasons renounce to optimize the lateral and out of plane behaviour of the arches ending up with very heavy and cumbersome sections needed to provide enough lateral stability.

3. Foundations and boundary conditions

The new bridge is located in the large Po River alluvial plain, about 30 km upstream of the river mouth. The subsoil of the alluvial plain is constituted by several hundred meters thick alluvial deposits. The surface portion of the alluvial sediments, directly interested by the bridge foundations, is formed by thin layers and lens of mainly clayey and sandy silts soils, with thin peat intercalations and some sandy layers up to 5-6m thick. Due to this geotechnical scheme, a strong base layer hasn't been considered in the pile foundation design, so that the bearing capacity has been largely assigned to the shaft resistance.

Three investigation campaigns, related to different project stages, have been conducted on site with core recovery boreholes (up to 50 m deep), SPT and vane tests and undisturbed sample collecting for laboratory tests. A complete laboratory campaign has been conducted, with triaxial, shear and oedometer tests, as well as physical properties determination. In order to have a complete geotechnical model of the subsoil, six cone penetration tests, with pore pressure measurements (piezocone –dissipation tests) have been also carried out.

On the basis of all the available investigation data, a specific and detailed geotechnical model has been drawn. The foundations are made of 1.5 m diameter bored piles. The length of the piles has been arrested to a depth of 35 m so as to avoid finishing in a soft layer encountered by the boreholes at a depth of about 40 m. The number of piles are, therefore, related to this limitation and to their lateral force resistance.

The foundation geometry has been conditioned by the presence of the existing bridge, which will be demolished before the construction of the new one, by the position of the new waterway and the course of the existing one, to be kept in service during construction works.

As far as seismic behaviour is concerned, several sand liquefaction phenomena were reported during the last earthquake which stroke the provinces of Modena and Ferrara in May 2012. Following specific analyses and investigations, risk of soil liquefaction has been ruled out for the specific site and foundation arrangement.

4. The steel structure

The arches and deck of the structure are made of 500 ton of steel (SJ355). Erection of the four arches and decks will be easily carried out by lorry mounted cranes especially since the larger span will be lifted in place before excavation of the new underlying channel.

At the time of going to press, colours and finishing of the steel carpentry are still to be finalised with the client. The white finishing that seems to be *de rigeur* in today architectural bridges has long lost its appeal to the authors and therefore something different is being investigated. The Cinerino (from the Italian word for ash, *cenere*) heron that inspired the design has a greyish colour and this is most likely a valid alternative, also one that is less prone to suffer from dirt and other weathering agents.

4.1 The arches

The arches of the two bridges are inclined 14^{o} to the vertical. This inclination cause only minor complication to construction and erection while increasing resistance against horizontal forces (wind and seismic action) and stiffness against buckling. The converging arch planes do also provide the structure with a more slender and elegant look.

The arch sections are of the double T type with height varying from 700 to 1200 mm and flange width from 700 to 900 mm. Typical web thickness is 20 to 25mm while flanges go up to 50mm thickness.

Although closed (boxed) sections do have a much better behaviour under compression, their use in small bridges is awkward because their dimension are insufficient for manned inspection and consequently for placing the hanger anchorages inside. If one adds the extra cost of fabricating a boxed section with respect to a standard double T section, the latter comes out much more convenient even if extra material needs to be added to achieve the same load carrying capacity.

Finally, load carrying capacity with respect to lateral and torsional buckling is certainly improved by the use of boxed sections but also by the cross bracing arrangement. Recently cross-bracing seems to be out of fashion and all sorts of arched structure are proposed that try to eliminate altogether this fundamental component of the twin arch configuration. Phoenix will sport a traditional K bracing made of steel tubes up to 400 mm diameter. Buckling analysis of the structure confirmed the strength and toughness of the chosen configuration with a load multiplier for the first buckling mode in excess of 7.

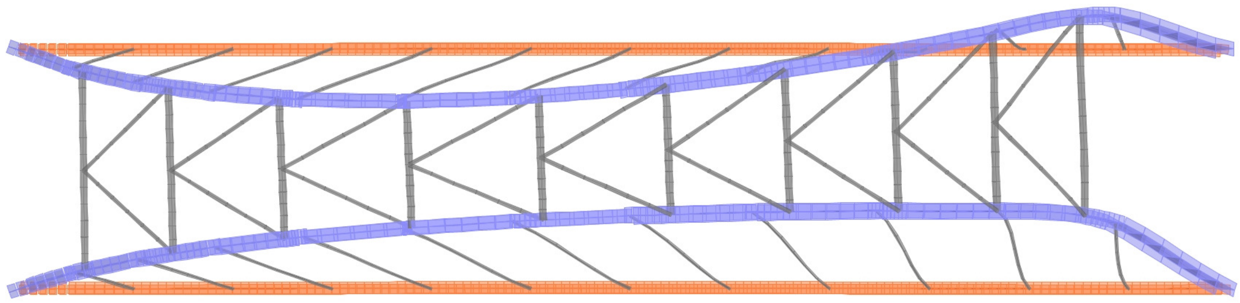

Fig. 5: First buckling mode of the larger arch

4.2 The deck

The bridge is 15 m wide with a 9.5 m road platform, a maintenance passage on one side and a larger pedestrian /cycle corridor on the other. The deck is supported on a grillage made of two longitudinal steel beams, 1000 mm high, and transverse steel beams at 3 m centre. The longitudinal beams have the same inclination of the arches but with their flanges resting on an horizontal plane so as to simplify the cross section geometry.

The deck slab will be cast on corrugated galvanised steel sheets. Transverse beams are rigidly connected to the deck slab so as to enforce composite action under positive (sagging) bending moments. In order to reduce the axial force that goes into the concrete slab, the latter is rigidly connected to the longitudinal beams only at the central piers where longitudinal forces are transmitted to the large pile foundation. Along the rest of the deck, the slab is cast 1m short of the lateral beams, just under the pedestrian corridor, thus leaving abundant and accessible space for utilities.

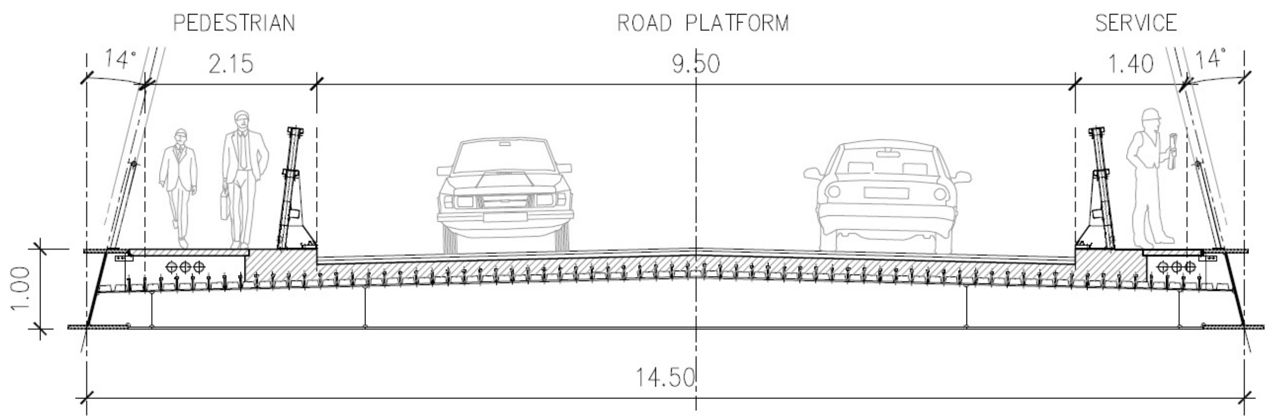

Fig. 6: Bridge cross section

4.3 The hangers

The real savings one can introduce in arch bridges is in the hanger's technology. When we think about hangers we imagine something of adjustable length and with pin connection so as to minimize parasite bending moments in the arches. Ropes, cables and bars can provide these features although they are enormously expensive and their price often a multiple of their actual production cost. In effect, while adjustable length is a very nice feature, pin connection is hardly indispensable since bending moment that can be carried by the hangers and passed onto the arches and deck generally negligible. As a matter of fact, various small arch and bow string bridges do use today hangers made of standard steel profiles, supposedly for the above mentioned reasons.

In the Phoenix case, hangers made of steel profiles not only are cost effective but do also enhance the structure resemblance to a bird as they are purposely featured so as to recall wing feathers. In order to simplify installation, hangers are bolted onto the arch webs and then tensioned to length and welded onto a gusset plate attached to the girder webs.

5. The FRC deck slab

Although it is now over 20 years that FRC is available and its use now codified by various international codes, its application in engineer structures is still scarce to say the least. An Italian colleague of us once said FRC is still in "*search of an author*", paraphrasing the title of a very famous Pirandello piece [2]. The authors believe there exists various situations where its use its highly beneficial. One example are the concrete anchorages of stayed and post/pre tensioned girders [3]. Everywhere we have very high stress gradients, FRC is the only solution to avoiding concrete cracking since normal reinforcing cannot be activated. An application of FRC to a stay cable bridge is being presented at this conference [4].

Another interesting application of FRC to bridges is in the deck slab [5]. Concrete deck slabs often make up the majority of the composite girder self weight. Given the upfront construction cost and other maintenance problems found with orthotropic steel decks, the possibility of optimizing the concrete deck slab performance and weight look very promising. In a tied arch the advantage of FRC compared to normal concrete is even more evident since the deck slab is prone to cracking due to combined shrinkage and applied tension from the arches.

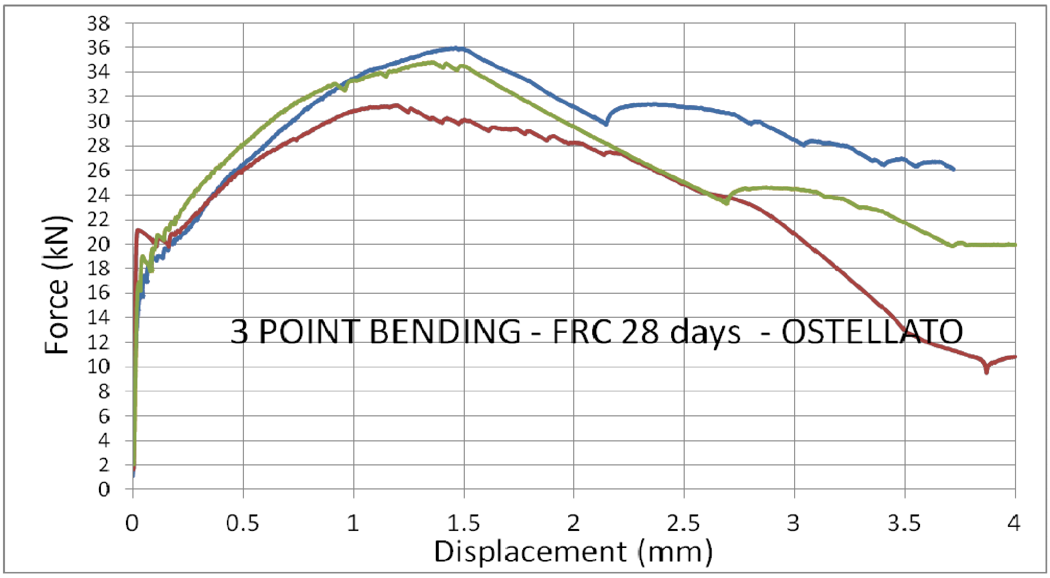

Fig. 7: Laboratory test of FRC notched beam

Use of FRC with a low fibre contents (30 to 50 kg/m^3) provide an easy and simple solution since these type of FRC are already widely used for industrial shelters and warehouses flooring. In case of bridge decks and stays/post-tensioning anchorages, fibre content can be increased up to 50 kg/m^3 still retaining the same procedures for mixing and casting. The test results obtained with 50 kg/m^3 of steel fibres in the nearby Ostellato stay cable bridge are very impressive. Tensile resistance and ductility of these type of concretes dramatically reduce the risk of cracking although do not eliminate the need for standard reinforcement that benefits from the increased bond properties of FRC. The amount of reinforcement can be significantly reduced though, making rebar assembling and concrete casting much easier and with reduced risk of segregation.

The increase of strength and toughness (ductility) of concrete that can be achieved with 50 kg/m^3 of steel fibres is amazing. The result of a 3-point bending test carried out on 150 mm notched [6] specimen plotted in Fig. 7 shows a dramatic increase in strength and toughness compared to the same standard concrete (class C32/40 with f_{ck} = 40 MPa) used for the FRC. Equivalent tensile strength at peak load is 8 MPa circa. With this increase of the tensile properties and ensuing bond capabilities, crack opening of the slab should be negligible since toughness (energy required for cracking) is an order of magnitude greater than that of standard concrete.

6. Conclusions

Tied arch bridges can be cost competitive and aesthetically appealing only if the structural behaviour is optimized so as to reduce member seize and weight. The structural optimization requires the arches to follow the load funicular, leaving therefore only minor room for variations in their shape.

Contrary to most of the experiments seen so far where designers have been inclining and rotating the arch planes, the proposed design stem out of the modification to the arch funicular generated by inclining the hangers within the arch planes that are kept in the optimal position, say vertical or slightly converging. The structural behaviour remains close to optimal but the arch profile changes dramatically opening up new possibilities for architects and designers.

The proposed bridge sports a number of other features that help improving slenderness, structural efficiency and cost competitiveness, namely: 1) arch and beam section are of the open type, easy to fabricate, assemble and inspect; 2) deck slab is made of FRC, with low fibre content plus standard reinforcement, to minimize the risk of cracking due to shrinkage and tie action; 3) hangers are made of welded steel profile thus reducing the cost of costly bars and ropes.

Construction works are due to start at the time of going to press.

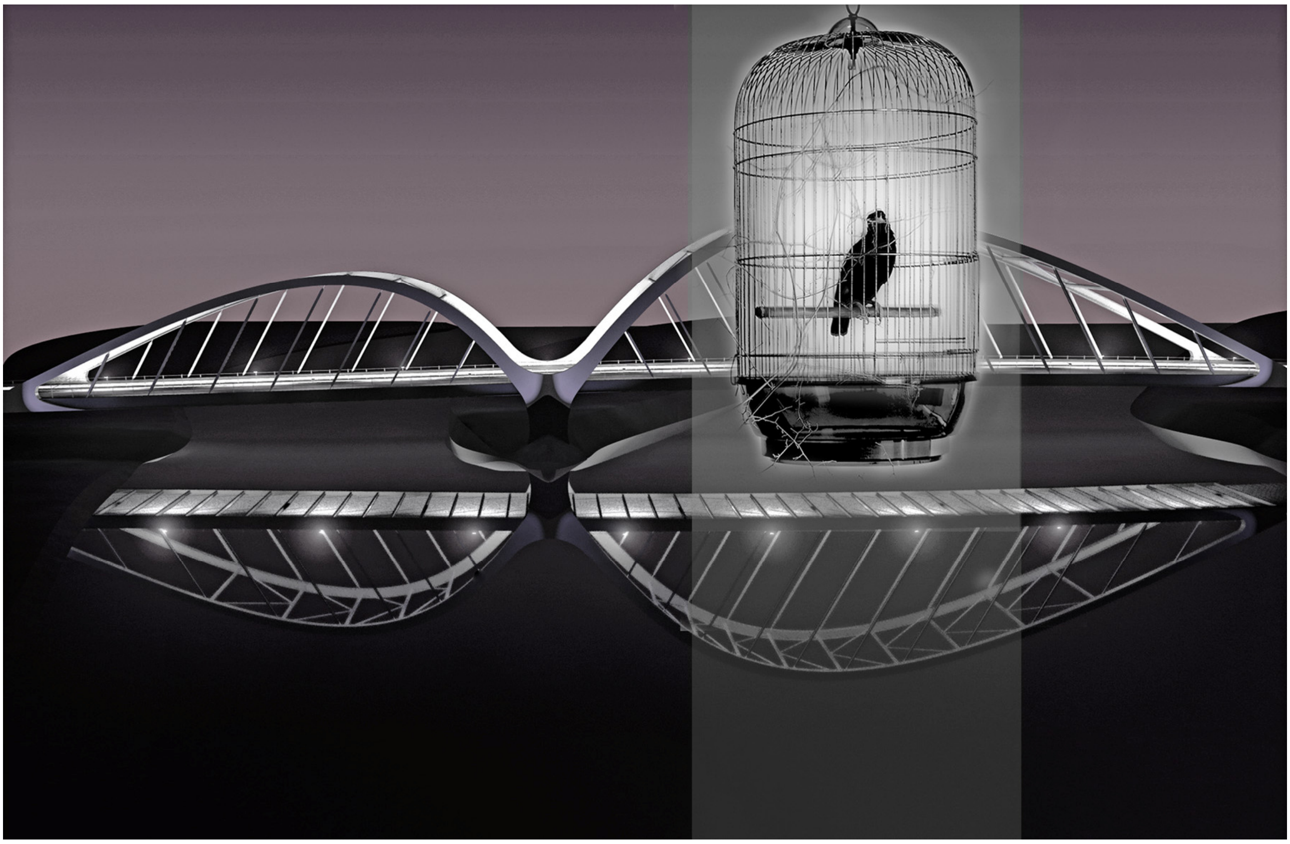

Fig. 8: A render of the bridge with artist intervention

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