Bridge Engineering
Volume 169 Issue BE1
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Pipinato

ice | proceedings

Proceedings of the Institution of Civil Engineers
Bridge Engineering 169 March 2016 Issue BE1
Pages 54–66 http://dx.doi.org/10.1680/jbren.14.00013
Paper 1400013
Received 10/03/2015 Accepted 21/08/2015
Published online 08/10/2015
Keywords: bridges/fatigue/stress analysis

ice
Institution of Civil Engineers
publishing

Structural analysis and design of a multispan network arch bridge

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This paper presents a study of a typical 1·1 km bridge in the north of Italy against a background of new infrastructure development. The bridge is composed of five network steel arches. The design solution represents a lightweight alternative if compared to traditional arch bridges. Every network arch spans 130 m, is 17 m wide and has a maximum height of 25·5 m. The deck is a steel–concrete composite section resting on precast slabs. Hangers have a variable inclination according to the geometric optimisation analysis performed. Before the final structural design, parametric studies were developed in order to optimise the material grade, the structural shape and the structural detailing.

Notation

$\Delta\sigma_1$	stress range
$\Delta\sigma_{E2}$	equivalent constant amplitude stress range related to maximum number of cycles
λ	equivalent damage factor
λ_1	traffic damage factor, depending on the critical influence line
λ_2	traffic intensity factor
λ_3	lifetime factor
λ_4	factor depending on the traffic on the other load lines
λ_{max}	a maximum level of λ
ϕ_2	equivalent factor

1. Introduction

The network arch bridge presented in this paper (Figure 1) is one of the first typical bridge design applications of the author's research on innovative structures in steel bridges. The research has investigated two principles: the use of high strength materials and structural optimisation in medium span steel bridges. With regard to the first aspect, high strength steel has achieved much use in the market of steel structures; for example, the S355 steel grade was considered a high strength steel grade only 20 years ago, whereas now it is the predominant grade for hot rolled plates throughout Europe. Moreover, other advanced steel grades are available in the market, such as S420 or S460, and the standardisation deals with up to S960 grade (Aalberg and Larse, 2000; CEN, 2005a; EN CEN, 2007; Collin and Johansson, 2006). It has also been demonstrated that new materials are able to influence weight reduction positively in bridges, reducing the costs of raw materials and of construction, and the energy consumption. Network arches represent the most promising solution for medium span bridges; this quite unusual shape has been investigated in the past by some authors and engineers, but has rarely been applied. The hangers are inclined, with multiple intersections, making the network arch bridge act like a truss, with only axial compressive and tensile forces prevailing, and with bending moments and shear forces remaining at very low levels. Accordingly, the number of hangers, their inclination and distance, are different for every type of structure as these are parametrically defined according to the load, the road type and the geometry of the deck. Because both the arch and the tie are mainly subjected to axial forces, their cross-sections can be very small. Another typical characteristic of network arches is that transverse bending in the deck is greater than bending in the longitudinal direction; therefore, a concrete deck that spans between the arches is a good solution for bridges with arch distances that are not too large. The concrete deck usually has longitudinal prestressing tendons in the arch planes. For these reasons, a network arch bridge with a high grade steel has been chosen as the design solution.

2. Code aspects

EN codes have been adopted in the design of this bridge; in particular, CEN (2006a) for the design of steel members and CEN (2006b) for the load assumptions. Welding connections are planned to be performed for tube–arch connections; specific testing on welding connections will be provided in the executive design phase, in order to comply with code specifications, and to test the specific fatigue endurance (see also EN 1993-1-9). With regard to national coding, the use of a national technical code (MIT, 2008) is mandatory in Italy, but for special design projects such as steel bridges, use of the EN code is allowed.

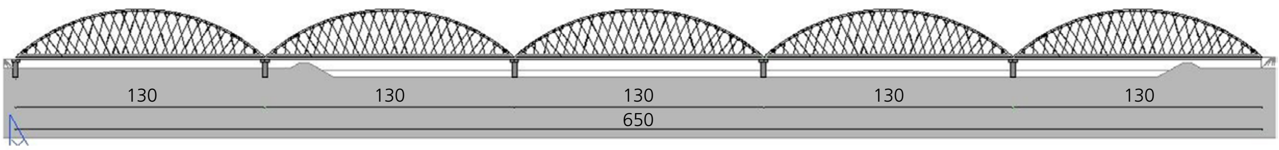


Figure 1. The multispan bridge across the Po river, lateral view

3. Structural aspects

3.1 Introduction to network arches

The structural solution chosen is the network arch bridge, which is distinguished in its shape from traditional arch bridges by the geometry of the hangers, formed by a net of hangers instead of the classic vertical solution. These structures are mainly based on various publications and studies developed by Per Tveit (Tveit, 1966, 2010; Tveit and Pipinato, 2011). In the first stage of the network arch study and design, some of the hangers were not in tension for particular loading conditions (asymmetric). To avoid this and to optimise the model, the geometry was changed by the introduction of new hangers, and in this way all the hangers were in tension; consequently the structural steel and shape was optimal, the arch does not have instability problems and finally the bending stress on the deck is lower. While arches are usually made of structural steel, the deck could be constructed with a post-tensioned deck, with a concrete–steel mixed section, with a steel deck, or finally a combination thereof. One of the most efficient solutions is the post-tensioned deck, even if the structure should be chosen according to the design specifications and requirements. The geometry and disposition of the hangers are strictly related to the type of deck adopted; if an all-concrete deck solution is used, the design of the hangers could be varied along the deck without any fixed position being imposed by the geometry of the transverse beam in the steel solution. Some suggestions are given in the literature (Tveit, 1966, 2010; Tveit and Pipinato, 2011) in order to design the final shape of the structure. In this particular case, the latter solution was adopted because of the structural optimisation performed. The geometry/inclination of the hangers was given by non-dimensional numerical values related to the live load against dead load ratio and the live load against the bridge span. In order to understand this, a traditional arch with inclined hangers subjected to a non-symmetric loading could be considered; the hangers are alternatively in tension and compression (Figure 2). To optimise this model in order to have all the hangers in tension and a lower effect of bending on the chord, another series of hangers should be added, as described in Figure 3. By adding a new series of hangers, the benefits include a minor arch buckling value and minor bending effects on the chord and on the arch, developing a so-called network arch (Figure 4).

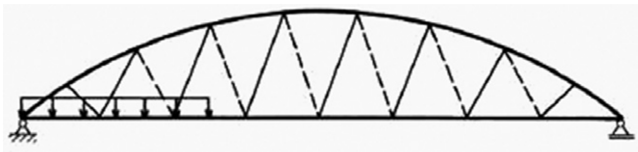


Figure 2. Traditional arch bridge with inclined strands with an asymmetric loading condition

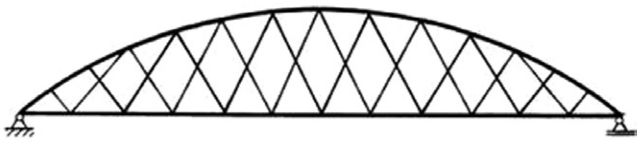


Figure 3. Arch bridge with a double net of inclined strands

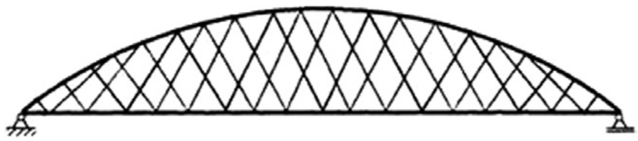


Figure 4. Network arch bridge

3.2 The project

The structural project described in this paper comes from research in which high strength steel network arch bridges were investigated. Among them, NA130 was a prototype for a network arch bridge spanning 130 m and built in S460 high strength steel. This prototype has been adopted in a typical multispan design bridge (Figure 5): the road is 10·5 m wide and the structure is 17 m wide, with a maximum height of 25·5 m ($h/s = 0{\cdot}2$). The plan and lateral view of a single arch is shown in Figure 6, while hanger and anchorage details are shown in Figure 7.

3.3 Structural description

The deck is made up of a composite steel–concrete section resting on *predalles* slabs. Transverse beams are made of variable height beams, to provide water drainage, resting 5 m from each other. The reinforced concrete deck slab has a thickness of 30 cm including the *predalles* used as formwork. The total cross-section includes a 10·5 m road dedicated to the platform, including two lanes of 3·75 m, lateral lanes of 1·5 m, and side areas of 0·75 m (to accommodate the barrier guard rails). It has the dual task of transferring, transversely to the main structure, the vertical road loads and collaborating with the main structure in the transverse direction. Hangers are built as tension hangers, with varied inclination according to the geometric optimisation performed, which is described in the following paragraph. The bridge substructure is made up of the abutment, carrying loads to the piles. Foundations rest on piles of 100 cm in diameter, 20 m long, resting on a compact sandy gravel. Before reaching the proposed structural design, parametric studies were performed in order to optimise the material grade, the structural shape (including hanger geometry) and structural detailing cost (welding/bolting).

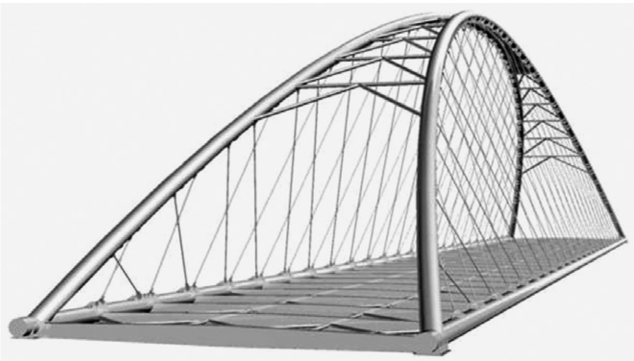


Figure 5. Three-dimensional view of one network arch span

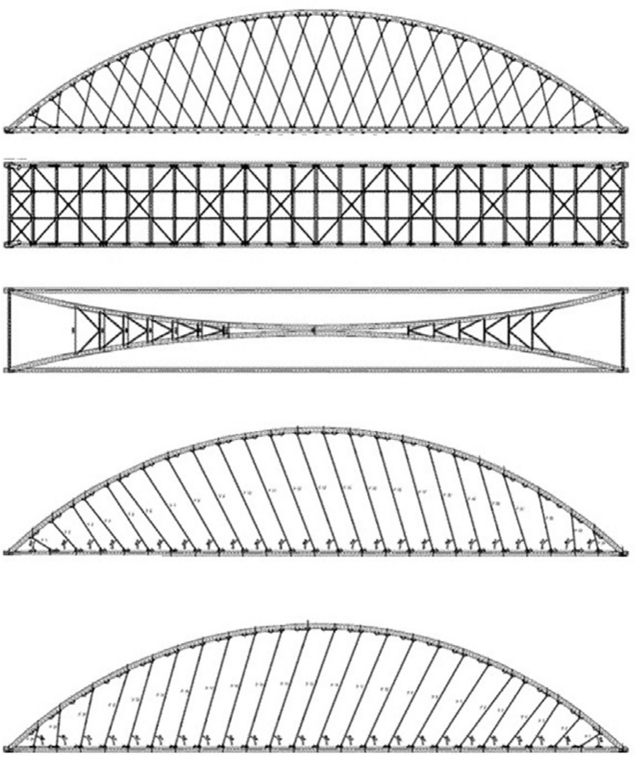


Figure 6. Lateral view, plan of a single arch, strand geometry

3.4 Steel members and finite element method design

The structural steel members are designed mainly at nearly the maximum of the design stress. In this way (Collin and Johansson, 2006), the strength can be fully utilised and the cost of materials is generally reduced as the strength is maximised. The design has also taken into consideration deck deformation, defining an optimised RC deck shape (see Figure 8). Finally, detailed investigations for bridge structural details, aimed at revealing stress concentrations, have been performed with separate submodels of the structure. One of the most stressed details is represented by the outer hangers; for this reason, sub-finite element method (FEM) models have been implemented in order to investigate peak stress regions and optimal shape definition for critical details. The geometry of one of these details is reported in Figure 9, whereas in Figure 10 and Figure 11 the details in the context of the principal structure and the stress levels highlighted by the analysis are presented. A full penetration welded connection is verified at the ultimate limit state, in accordance with the requirements of CEN (2005b), section 4.7.1, according to EN 1993-1-12 (CEN, 2007) principles. A detailed investigation, which is recurrent in these bridge types, involved the fatigue verification of hanger structures (Pipinato *et al*., 2009, 2011); particularly in these components peak stresses related to cyclic loads could be found. The geometry of one of these details is shown in Figure 11, while in Figure 12 the details in the context of the principal structure are outlined. In Figure 13 the stress levels highlighted by the analysis can be observed; also in this case a full penetration welded connection is verified at the fatigue serviceability limit state according to the EN 1993-1-9 verification procedure. Similar to this last verification, a specific investigation has been carried out for the arch-to-chord detail, in order to avoid stress concentrations by detailed FEM analysis and structural shape optimisation; some insights into this part of the structural design can be found in Figure 13. Finally, the construction alternatives have been studied; according to this investigation, the arch will be constructed subdividing the arch into five subsections, to be assembled by on-site welding (Figure 14).

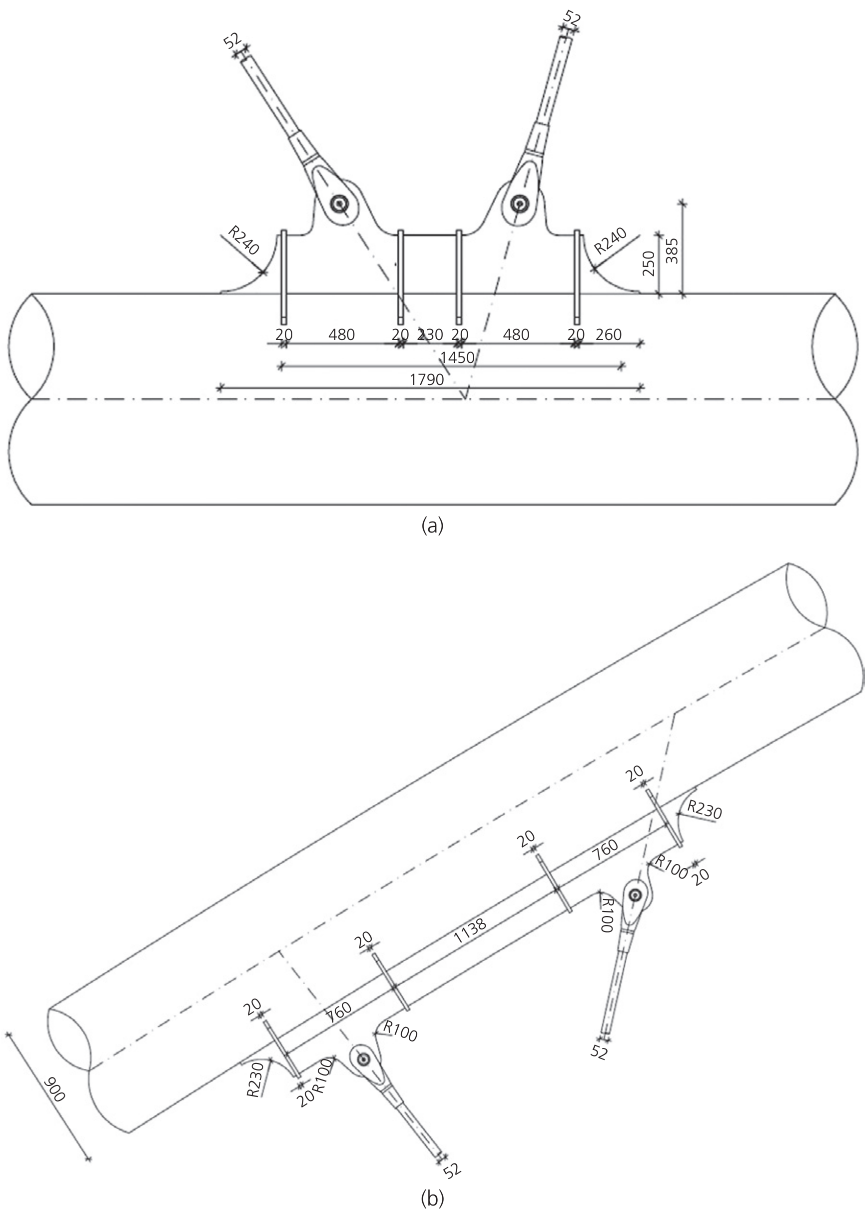


Figure 7. Hanger details: on the deck (a) and on the arch (b)

4. Parametric analysis of the hangers

4.1 Analysis

Different arch and hanger geometries have been studied in order to evaluate accurately the most effective design of the arch bridge in a parametric analysis, including the following solutions

- parabolic arch with two hangers for anchorages (Figure 15(a1) and 15(a2))
- circular arch with two hangers for anchorages (Figure 15(b1) and 15(b2))
- parabolic arch with one hanger for each transverse beam in the deck, and with a constant inclination of 60° (Figure 15(e))
- circular arch with one hanger for each transverse beam in the deck, and with a constant inclination of 60° (Figure 15(d))
- parabolic arch with one hanger for each transverse beam in the deck, and with variable inclination (three solutions) (Figure 15(e))

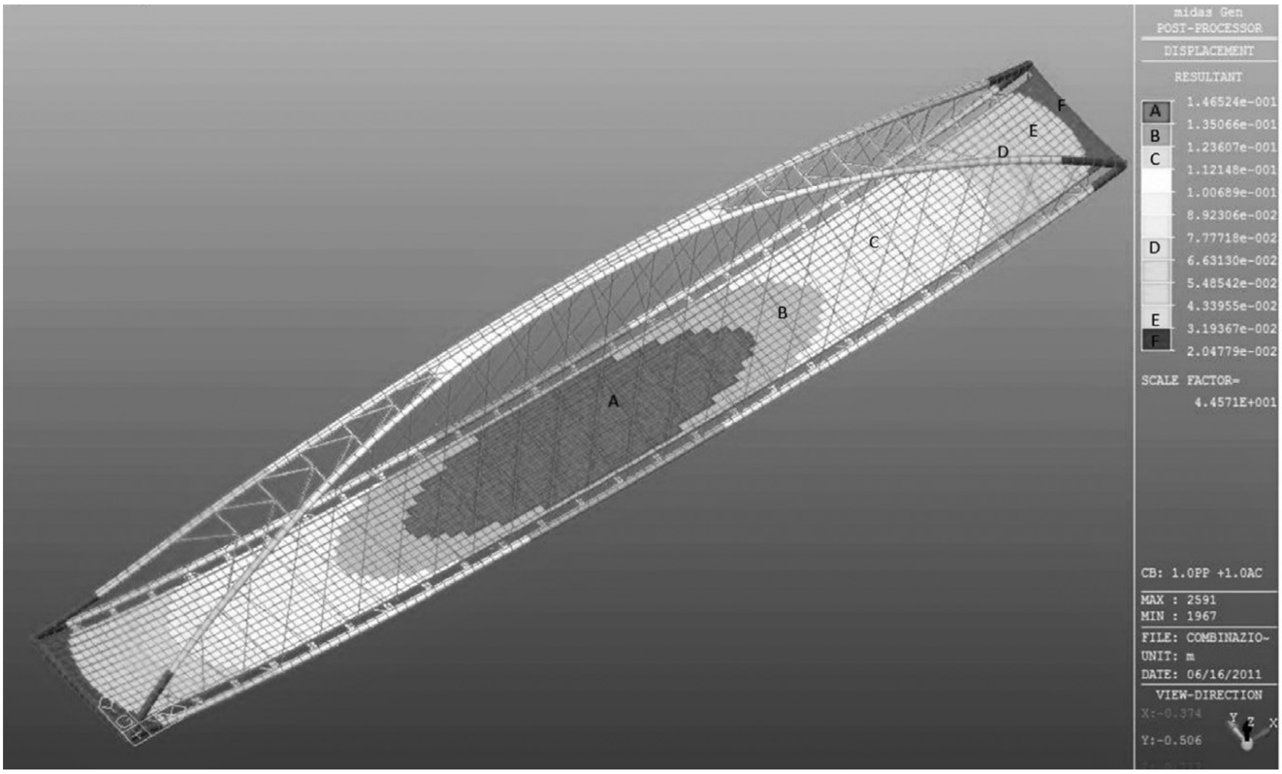


Figure 8. Deck displacement under vertical loads

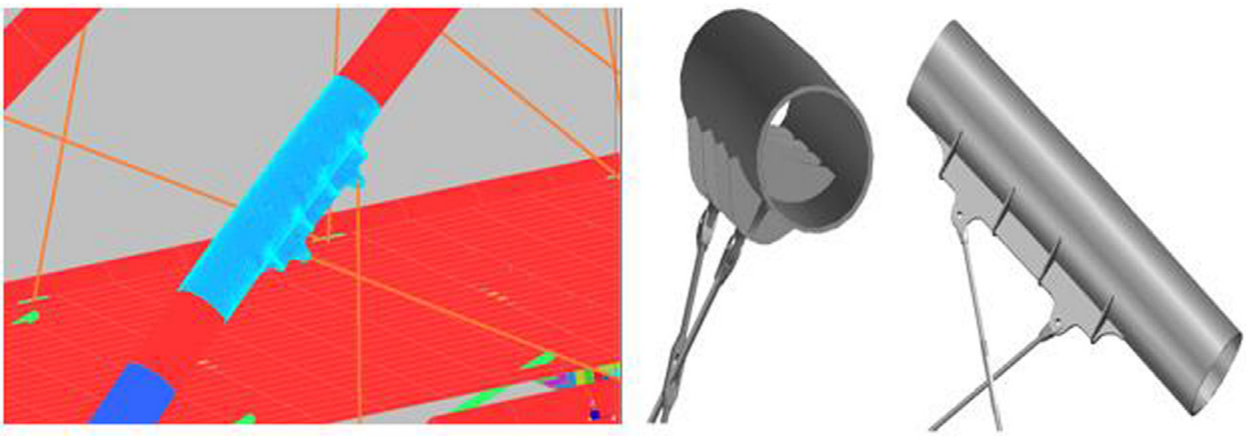
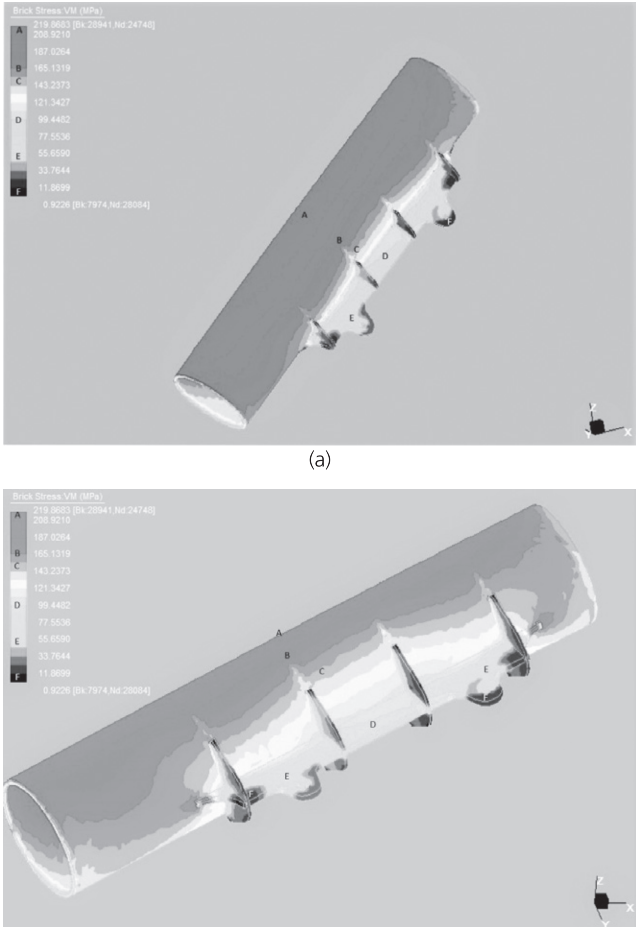


Figure 9. Detail of an arch hanger, finite element method and three-dimensional illustration

- circular arch with one hanger for each transverse beam in the deck, and with variable inclination (three solutions, 50 hangers) (Figure 15(f))
- parabolic arch with two hangers for each transverse beam in the deck, and with a constant inclination of 60° (Figure 15(g))



(a)

(b)

Figure 10. Detail of an arch hanger, stress analysis: (a) lateral and (b) bottom view.

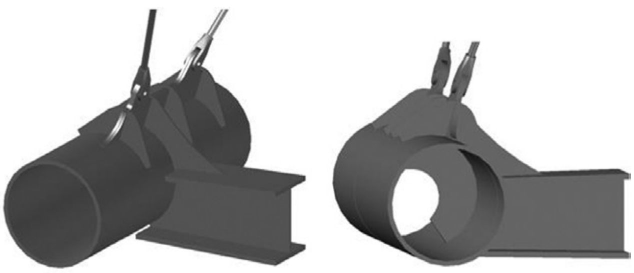


Figure 11. Hanger-deck detail

- circular arch with two hangers for each transverse beam in the deck, and with a constant inclination of 60° (Figure 15(h))

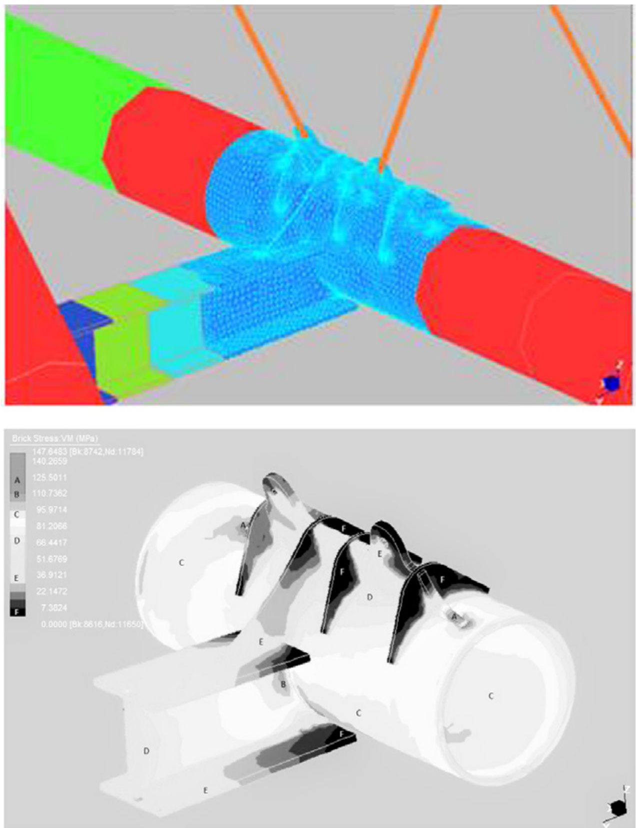


Figure 12. Detail of a deck hanger, finite element method and stress analysis

- parabolic arch with two hangers for each transverse beam in the deck, and with variable inclination (two solutions) (Figure 15(i))
- circular arch with two hangers for each transverse beam in the deck, and with variable inclination (two solutions) (Figure 15(j))
- parabolic arch with two hangers for each transverse beam in the deck, and with a constant inclination of 60° (Figure 15(k))
- circular arch with one hanger for each transverse beam in the deck, and with variable inclination (two solutions, 48 hangers) (Figure 15(l)).

4.2 Discussion

The circular arch represents for this particular geometry the most effective solution with two hangers for transverse beams and with variable inclinations, for the following reasons

- the distribution of hangers and relative hangers on the deck is constant in the deck, with an improved global stability of the arch

- at the same time, a constant distribution of hangers in the deck is more convenient from the construction point of view
- two hangers for each transverse beam gives a more rigid connection for the transverse beam itself, with an inversion of the bending moment, and at the same time lower tensions in the deck can be observed
- all hangers remains in tension only
- the bending moment distribution on the arch is regular, and peak stresses are avoided in this configuration
- the circular arch is easier to build and erect, presenting a single curvature.

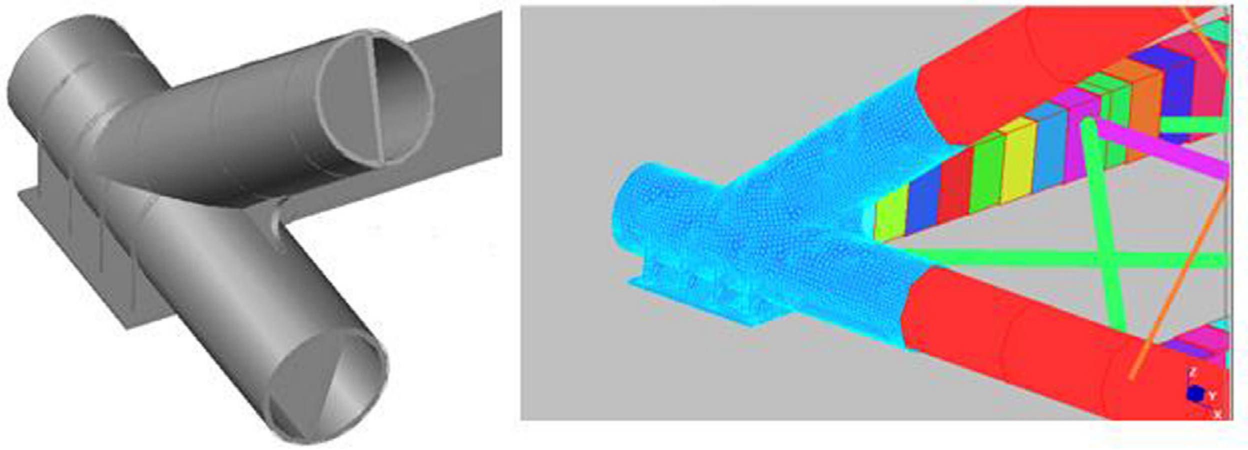


Figure 13. Detail of the arch footing, three-dimensional and finite element method

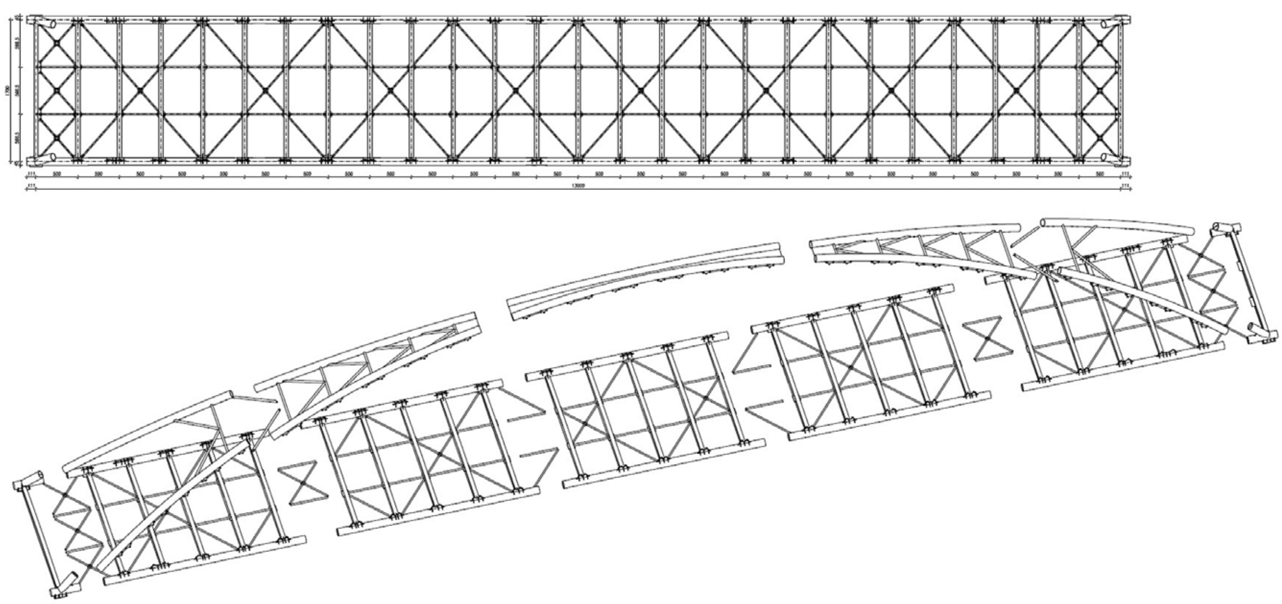
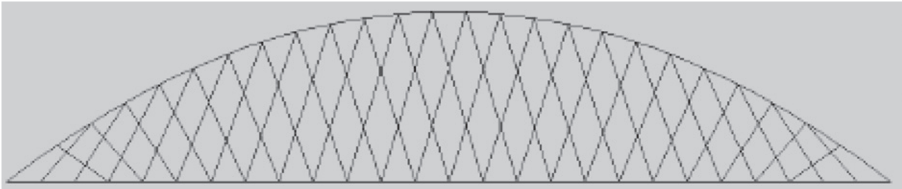
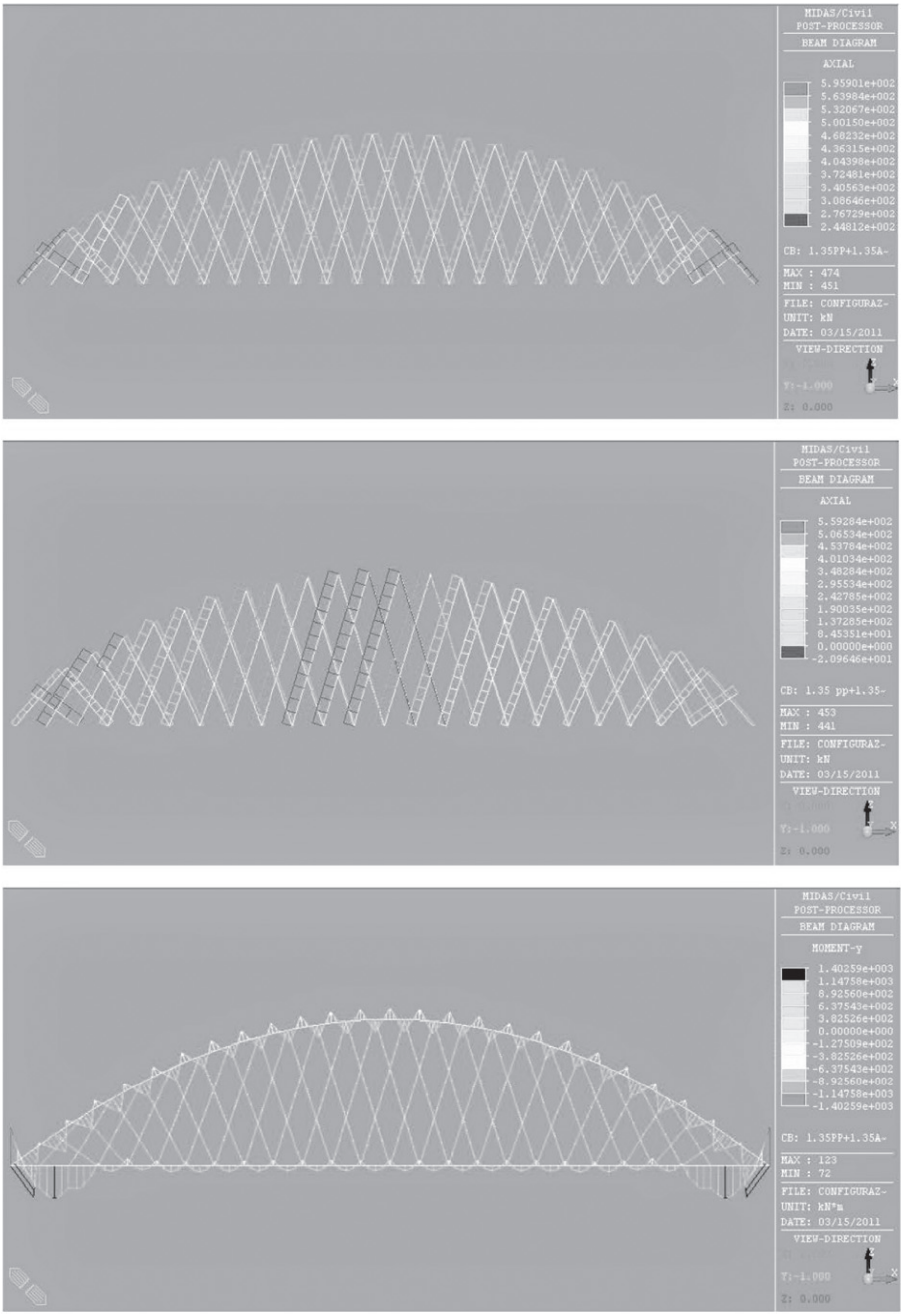


Figure 14. Deck view and three-dimensional view of the structural elements

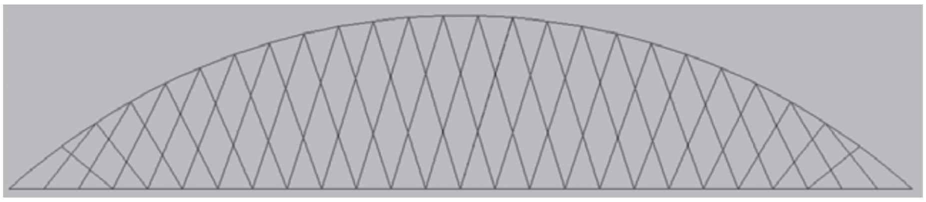


(a1)

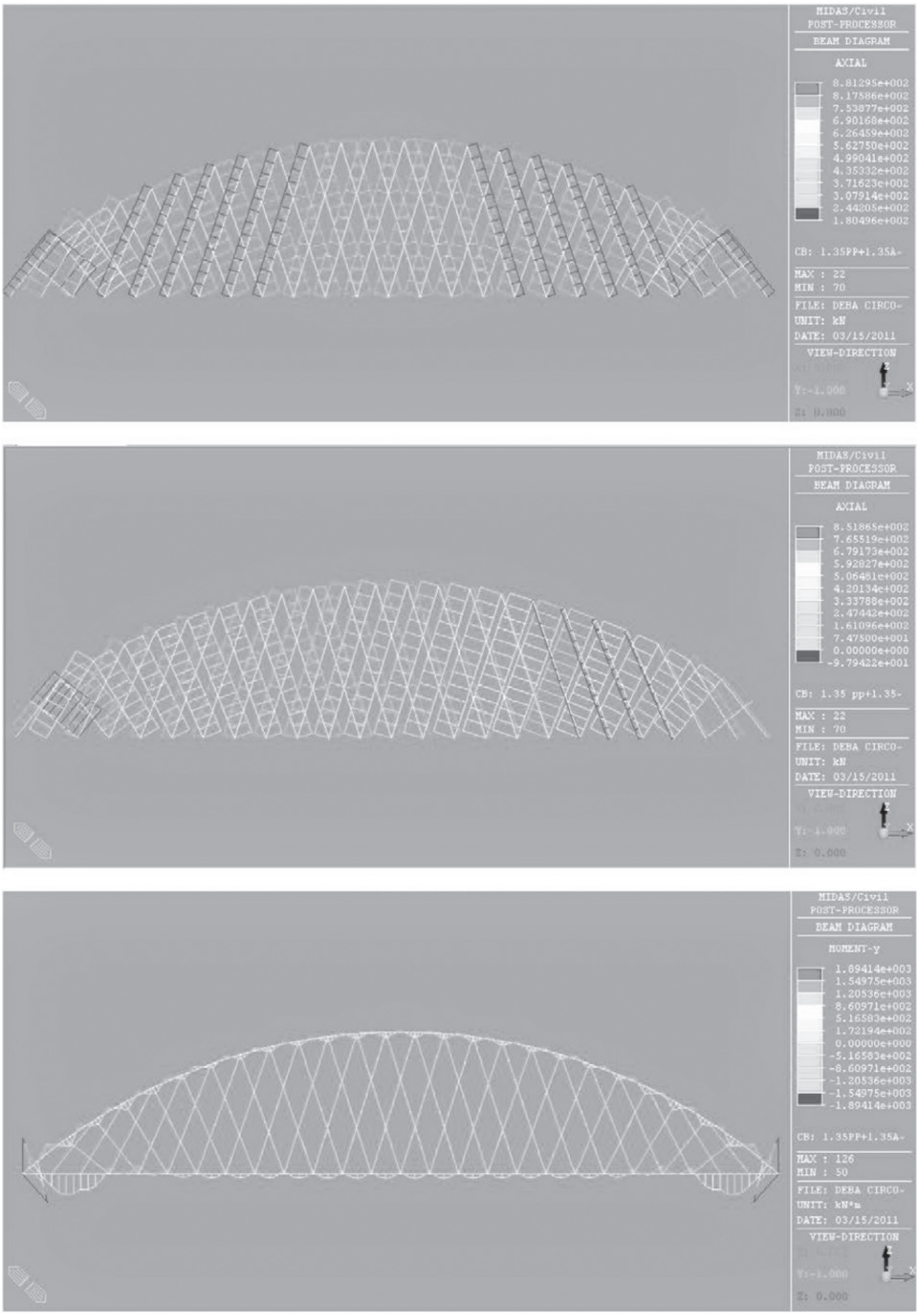


(a2)

Figure 15. Continued

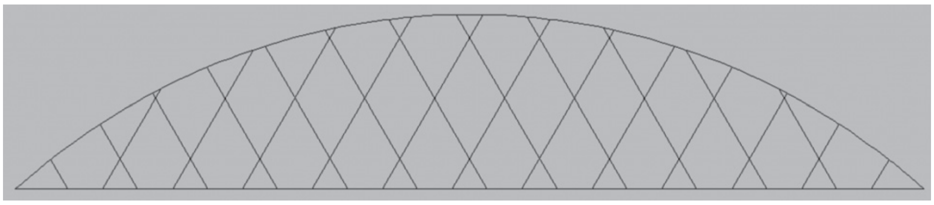


(b1)

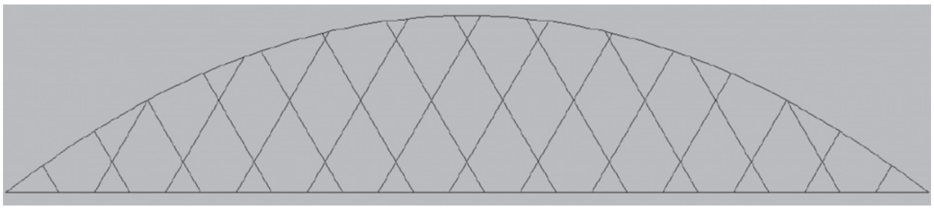


(b2)

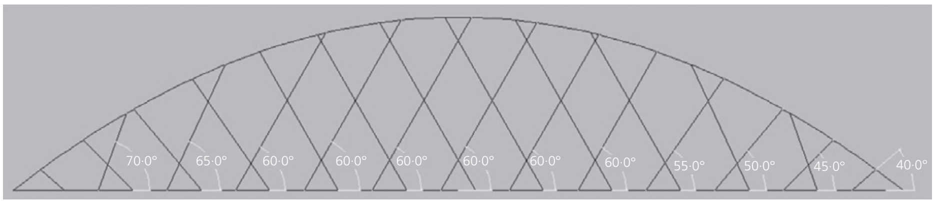
Figure 15. Continued



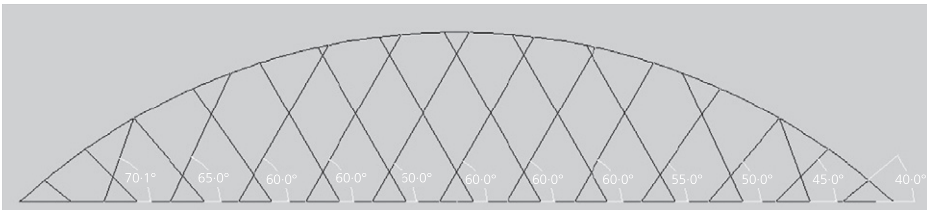
(c)



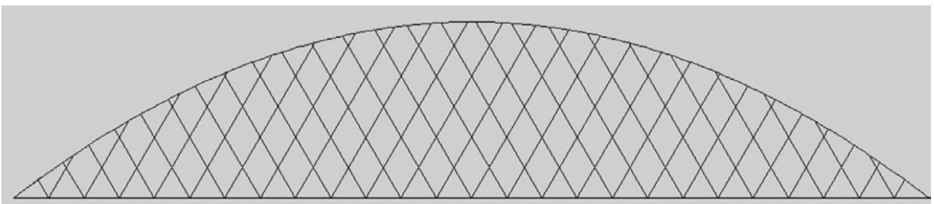
(d)



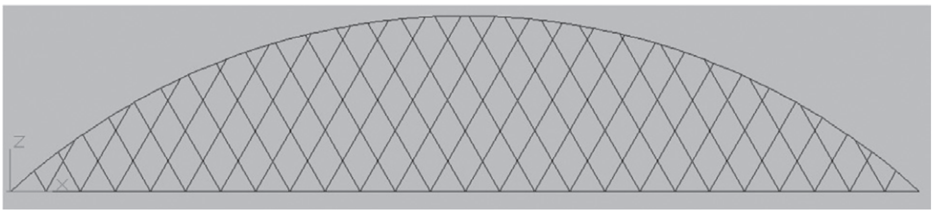
(e)



(f)

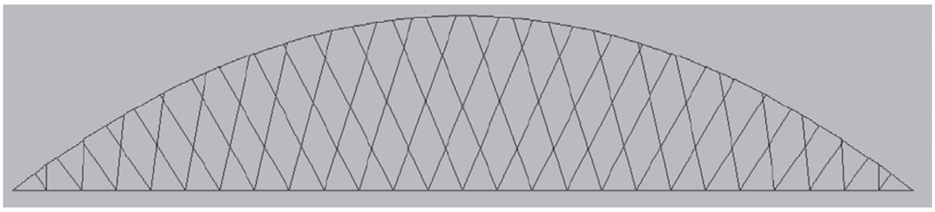


(g)

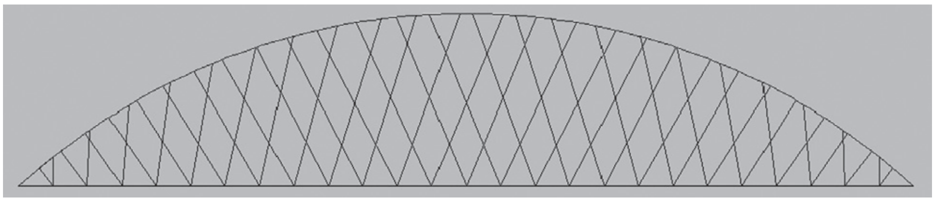


(h)

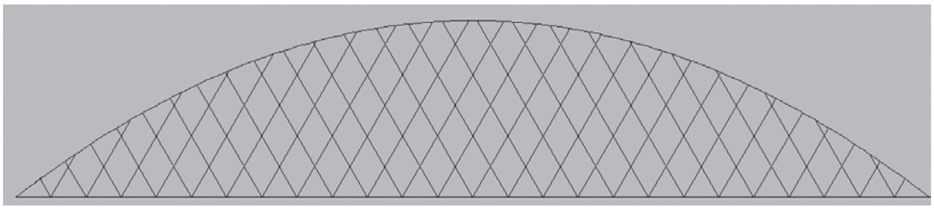
Figure 15. Continued



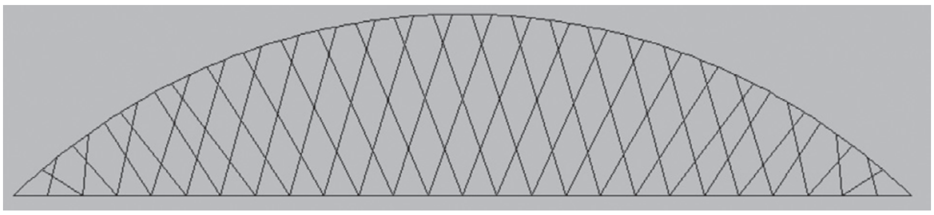
(i)



(j)



(k)



(l)

Figure 15. (a) Parabolic arch with two hangers for anchorages (a1 geometry; a2 stress analysis); (b) circular arch with two hangers for anchorages (b1 geometry; b2 stress analysis); (c) parabolic arch with one hanger for each transverse beam in the deck, and with a constant inclination of 60° geometry (d) circular arch with one hanger for each transverse beam in the deck, and with a constant inclination of 60°; (e) parabolic arch with one hanger for each transverse beam in the deck, and with variable inclination (three solutions); (f) circular arch with one hanger for each transverse beam in the deck, and with variable inclination (three solutions, 50 hangers); (g) parabolic arch with two hangers for each transverse beam in the deck, and with a constant inclination of 60°; (h) circular arch with two hangers for each transverse beam in the deck, and with a constant inclination of 60°; (i) parabolic arch with two hangers for each transverse beam in the deck, and with variable inclination (two solutions); (j) circular arch with two hangers for each transverse beam in the deck, and with variable inclination (two solutions); (k) parabolic arch with two hangers for each transverse beam in the deck, and with a constant inclination of 60°; (l) circular arch with one hanger for each transverse beam in the deck, and with variable inclination (two solutions, 48 hangers).

5. Fatigue analysis

5.1 Analysis

Fatigue analysis has been developed according to EN-1993-1-9 (CEN, 2007). The applied load is the FLM3 (EN 1991-2), consisting of a standard vehicle with 120 kN axles. The effects of the interaction of the vehicle on the bridge have been numerically calculated in order to obtain the maximum and minimum stresses and the corresponding maximum stress variations in key substructures

1. $$\Delta\sigma_p = |\sigma_{p,\max} - \sigma_{p,\min}|$$

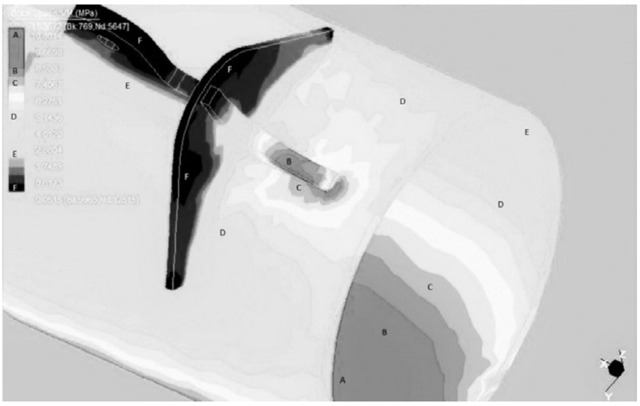


Figure 16. Hanger-to-deck connection detail: fatigue analysis

From $\Delta\sigma_p$, the equivalent damage at 2 million cycles could be evaluated according to the Eurocode procedure

2. $$\Delta\sigma_{E2} = \lambda\phi_2\Delta\sigma_p$$

where λ is the equivalent damage factor; ϕ_2 is an equivalent factor, which is 1 for road bridges

3. $$\lambda = \lambda_1 \times \lambda_2 \times \lambda_3 \times \lambda_4 \leq \lambda_{max}$$

where λ_1 is the traffic damage factor, depending on the critical influence line; λ_2 is the traffic intensity factor; λ_3 is the factor depending on the lifetime of the bridge; λ_4 is the factor depending on the traffic on the other load lines; and λ_{max} is a maximum level of λ.

5.2 Discussion

This analysis has been performed for various details, including the following that are mentioned here as the most relevant

- the welding connection of the transverse beam to the deck, a very critical fatigue point as the live loads are carried on the arch, and moreover, considering every vehicle passing over the transverse beam as one damage cycle (category 80)
- the transverse beam itself, analysing the possibility of making the same as a built section or as a standard section (category 112); also in this case, the increasing damage is accumulated for every single passage of a vehicle
- the cover plating of the transverse beam (category 40)
- tension hangers – arch connection, constructed with longitudinal plates (category 80) (Figure 16): this connection is built with longitudinal filleted plates.

The most stressed detail has been considered in every analysis, applying the fatigue load model in order to maximise/minimise the stress state. Critical details to fatigue have been solved by incrementing the welding connection length or changing the geometric shape of the details, or finally adding stiffening plates in key sections in order to redistribute the stress state. As a result of these improvements, peak stresses have been avoided and the flows of forces have been redistributed.

6. Conclusion

In this paper a multispan network arch bridge has been presented and analysed, in the case in which a long span solution was not adopted. The structural typology and the material choice have been made according to past studies and research of the author. Accordingly, the material chosen has been a S420 construction steel, and the typological solution a network arch bridge, a quite unusual bridge shape but with interesting characteristics in terms of weight reduction and structural performance. The paper has considered all the design phases, from the choice of shape to the detailed analysis of the structures. As determined from the studies, this solution should be preferable for bridges in the 100–150 m span range, in order to achieve lighter structures that can be built faster, and providing a very simple geometry with fewer construction problems. The higher grades of steel and the steel–concrete composite section are key solutions to obtain a lightweight structure with a longer life. If compared to steel-only decks the composite alternative is an improvement, protecting deck steel components of the arches. The parametric studies illustrated and developed could be considered a time-consuming procedure, but as demonstrated, they are very useful in order to keep control of the weight design alternatives. The increased design time is certainly balanced by a more efficient and lighter solution.

Acknowledgements

FEM investigations and design have been conducted with the support of Eng. A. Bozza, A. Doglio, S. Baggio and F. Spiller.

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