HIGH STRENGTH STEEL BRIDGES: THE EUROPEAN EXPERIENCE

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BIOGRAPHY

Alessio Pipinato, Dr. Eng. Arch., after earning a master degree in Building and Structural Engineering at the University of Padua, the PhD in Design of Structure at University of Trento and a second master degree in Architecture in Venice, has started an intensive research program in the field of steel bridge engineering during the post-doc position period, participating also in real scale bridge experimentations. He has taught Building Construction and Bridge Design at the University of Padova. He has been selected at international and national level gaining prizes as the Piccinato Prize 2005 and 2007 as Selected Finalist, and he has also been selected as finalist at the World Archiprix International 2005; he was in the 3rd design group for the preliminary design of the "Palazzo del Cinema in Venice" in 2005. He has worked for design studios and engineering companies worldwide for the project of infrastructures, civil and public building and bridges. In the context of bridge design, he has being involved in the design and assessment of foot bridges, road and railway structures, and in particular he has deepen the design of net arch bridges, cable stayed and rc-steel composite decks. He is referee for international peer reviewed studies and research, serving also the ASCE Journal of Bridge Engineering. Author of more than 120 published studies in international and national journals, books and articles.

SUMMARY

Over the past decades high strength steel-HSS have become of relevant importance in the market of steel bridges and constructions. For e.g. past grade of HSS as S355 (EN 1993, 2005) are nowadays commonly employed also in minor bridges. New products of HSS are increasingly gaining ground in the market of bridge construction. As a result, research and design practice are been involved in this new common situation related to the choice of the most fitting material to create economical designs. Dead load plays an important role in the design of bridges and it is therefore of relevant importance to apply the optimum steel grade in order to minimize weight and reduce the construction costs. The paper focuses on the presentation of some relevant bridge design in HSS.

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Introduction

High strength steel has gained a large employment on the market of steel structures: for e.g. the S355 grade was considered a high strength steel grade only 20 years ago, while nowadays it is the predominant grade for hot rolled plates throughout Europe. Moreover other advanced steels grading are available in the market, like S420 or S460, and the standardization deals up to S960 grade [2]. In most applications, not only the cost reduction is a relevant aspect, but also the weight reduction is an important advantage because the payload can be increased or the running expenses decreased. Moreover, an increasingly important concern is the environment and more specifically the use of energy and raw material. In the present paper, are presented high strength steel products commonly employed in the infrastructural market in Europe, then code aspects are illustrated with reference to Eurocodes, while in the last part applications and case studies related to the topic of high strength steel bridges are presented: the first case is a network arch road bridge spanning 75m, coming from a design application; the second, is a prototype structure, realized in the context of a research project, aiming at the realization of a light structure steel bridge of 130m span in S460.

High Strength Steel Products

High yield strength steels (or high resistance, High Strength Steels-HSS) generally shows a useful ductility and weldability for the construction of structures, with a grading yield ranging from 420 up to 690 MPa, with elongations between 15 and 20%. The main categories are: high-strength micro-alloyed steels (also called HSLA); steels carbon - manganese (used for plates and / or profiles); heat treated carbon steel; low alloy steels heat-treated (used for tubular profiles). Steels produced with this method are called "thermo mechanical steels." The use of thermo mechanical steel (TM), compared to normalized (N), has the double advantage of having more mechanical strength combined with improved weldability (eg. possibility of eliminating preheating). The structures optimization aims to a substantial reductions in weight and fabrication cost and time, ensuring at the same time performance requirements, safety. Industrialized process lead to the product realization also of 1100 MPa grade, even if code indications (EN 10025-6) deals up to 960 MPa grade.

Code Aspects

Eurocode standards recognize the responsibility of regulatory authorities in each Member State and have safeguarded their right to determine values related to regulatory safety matters at national level where these continue to vary from State to State. In particular, EN 1993-2 is the second part of six parts of EN 1993 – Design of Steel Structures – and describes the principles and application rules for the safety and serviceability and durability of steel structures for bridges. EN 1993-2 gives design rules which are supplementary to the generic rules in EN 1993-1-1. EN 1993-2 is intended to be used with Eurocodes EN 1990 – Basis of design, EN 1991 – Actions on structures and the parts 2 of EN 1992 to EN 1998 when steel structures or steel components for bridges are referred to. EN 1993-2 is intended for use by committees drafting design related product, testing and execution standards, clients (e.g. for the formulation of their specific requirements), designers and constructors, relevant authorities.

In the framework of EN 1993 Eurocode 3: Design of steel structures, CEN TC250 SC3 was appointed as working group with the task to develop rules to make EN 1993 applicable to high strength steels. After a first draft (prEN 1993-1-12), the final version of the code was published in 2007 as EN 1993-1-12-2007 Design of steel structures - Part 1-12: Additional rules for the extension of EN 1993 up to steel grades S 700. The code rules is made up of test results and comparison with normal strength steel. However the general behavior of members is adequately covered, for some type of connections there are no test results.

Steels type covered are those according to EN 10025-6 and 10149-2, embracing:

- quenched and tempered steels delivered as flat plates, with ranging grade from S500 to S690; only material standard goes up to S960;
- TM steels for cold forming, with ranging grade from S500 to S700, usually delivered in coils and with thickness limited to 16mm

Regarding the requirements on material ductility, while for normal steel grade coded in EN 1993-1-1 recommended value of $f_u/f_y>1{,}10$ with elongation at failures not less than 15% ($\varepsilon_u > 15\ f_y/E$), for HSS steel grade coded in EN 1993-1-12 recommended value of $f_u/f_y>1{,}05$ with elongation at failures not less than 10%. Restrictions on steel structures fulfilling those requirements are mainly that plastic analysis and semi-rigid joints should not be used.

Concerning welding operation, undermatched electrodes are suggested, making welds more ductile and less prone to crack. These specific electrode are not allowed in EN 1993-1-8, while are allowed in EN-1993-1-12 for particular steel grades. Design according to this type of welding should be based on the electrode strength rather than the base material strength: this has been confirmed also in some recent studies [4].

About bolting connections, the main issues is related to the net section resistance. Concerning this issue, some studies have been developed by [5] with tests on S690 materials. As a consequence, for HSS this resistance in EN 1993-1-12 has not to be taken smaller than $f_y\ A_{net}/\gamma_{m0}$.

Concerning buckling, the code takes into considerations various studies in which the HSS structural performance resulted to be better than ordinary steels, or at least not worse: in EN 1993-1-1 this is taken into account in the rules for flexural buckling by the use of higher buckling curves for S460; EN 1993-1-12 states that these curves could be used also for higher grades.

Concerning the national coding, in Italy is up to now mandatory the use of a national technical code (*Norme tecniche per le costruzioni, 2008*), but for each special design aspect, concerning also steel bridges, it is admitted the use of EN. References for national structural steelwork are available since grade S460. The Eurocode adoption is admitted.

Application and Case Studies

In the present sections, two HSS steel bridge are presented. The first case is a network arch road bridge spanning 75m, coming from a design application. The second, is a prototype structure, realized in the context of a research design, aiming at the realization of a light steel bridge structure. Both applications are represented by network arch bridge, distinguishing their shape from traditional arch bridges for the strands geometry, that is formed by a net of cables instead of vertical hangers. These works are based mainly on various publications and studies developed by prof. Per Tveit [6-10]. In the following an introduction of this particular steel bridge is provided.

Introduction

In the first stage of the net arch study and design, some of the cables where not in tension for particular loading condition (asymmetric). To avoid this and to optimize the model, the geometry was changed, by the introduction of new cables, and in this way all the cables were in tension, consequently structural steel and shape was optimal, the arch doesn’t present instability problems, and finally the bending stress on the deck is lower. While arches are made up of structural steel, the deck could be realized with a post-tension deck, or as a concrete-steel mixed section, or finally as a steel deck. One of the most performing solution is the post tensioned deck, even if the choice of the effective structure should be related to the real design requirements. The cables geometry and the hangers disposition is strictly related to the deck type adopted: in fact, if a concrete deck is used, the hangers disposition could be varied along the deck without any fixed position that is imposed from the geometry of the transverse beam in the steel solution. Some suggestions are given in literature [5, 6, 7] in order to design the final shape of the structure. As a result, cables geometry/inclination is given by non-dimensional numerical values related to Live Load vs. Dead Load ratio and Live Load vs. bridge span. In oder to understand this, consider a traditional arch with inclined cables with non simmetric loading: cables are alternatively in tension and compression.

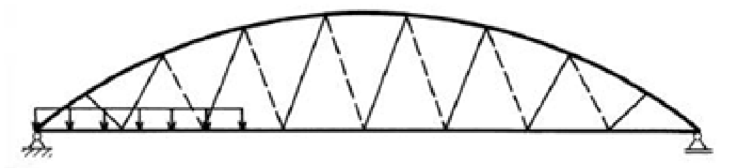

Figure 1: Traditional arch bridge with inclined strands with an asymmetric loading condition.

In order to optimize this model, aiming to have all suspension in tension and a lower effect of bending on the chord, you should insert another series of cables, like it is described in the following figure.

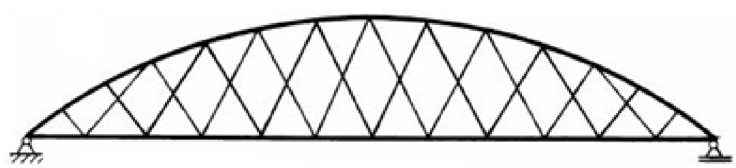

Figure 2: Arch bridge with a double net of inclined strands.

Adding a new series of cables, beneficial aspects includes a minor arch buckling value, and minor bending effects on the chord and on the arch, developing a so called network-arch.

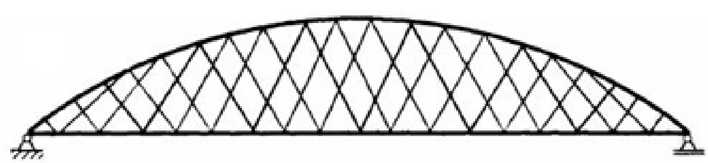

Figure 3: Network arch bridge.

a) NA75 bridge

The bridge spanning 75m is made up by two parallel steel arches with a constant radius of 100m, and an height of 12.75m; the arch force is counterbalanced by the inferior beam chord in which are connected the transverse beam of the road deck and the lateral foot passages. The deck is made up by a composite steel-concrete section, resting on the transverse with a constant span of 2.5m: this concrete deck is 25 cm thick resting on *predalles* slab used as formwork. The cross section is constant and 15.8 m large, 11.50 m dedicated to road traffic, with two lanes of 3.5m, two lateral lanes of 1.25 m and two lateral zones of 0.75 m dedicated to barriers. The principal constituent material are steel S420-J2 for steel structures and C35/45 for the concrete deck. The structure is made up of two arches linked with couple of cables to the deck, made up by transvers and of the composite deck. Bridge substructure is made up of abutments, carrying loads to the piles foundations; these are realized on piles of 100 cm of diameter, 35m long, resting on a compact sandy gravel. The reinforced concrete basement has a constant height of 2.4m.

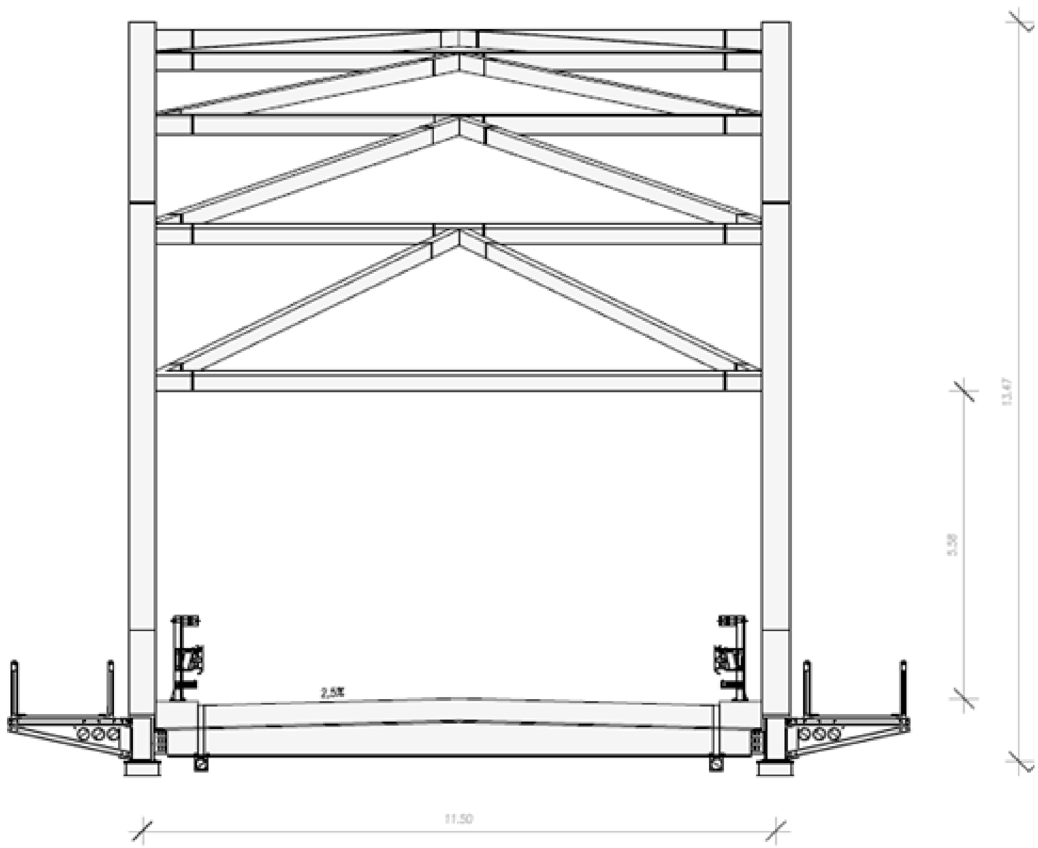

Figure 4: Front view of the bridge.

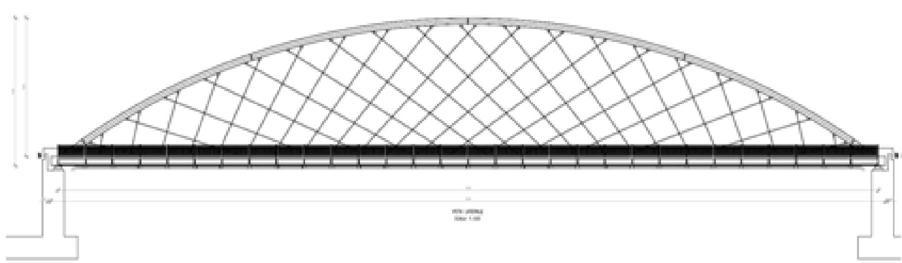

Figure 5: Lateral view of the bridge.

b) NA130 bridge

NA130 is a prototype for a network arch bridge standing for network arch spanning 130m completely realized in S460 high strength steel: it has been started as a research project on HSS bridges, and is now been launching as a design project; the road is large 10.50m, while the structure is large 17.00m, with a maximal height of 25.5m (h/s=0.2). The structure is completely realized with high strength steel grade S460. The deck is made up of a composite section steel-concrete resting on *predalles* slabs. Transverse are realized by variable height beams for drainage, and they are spanning 5m each other.

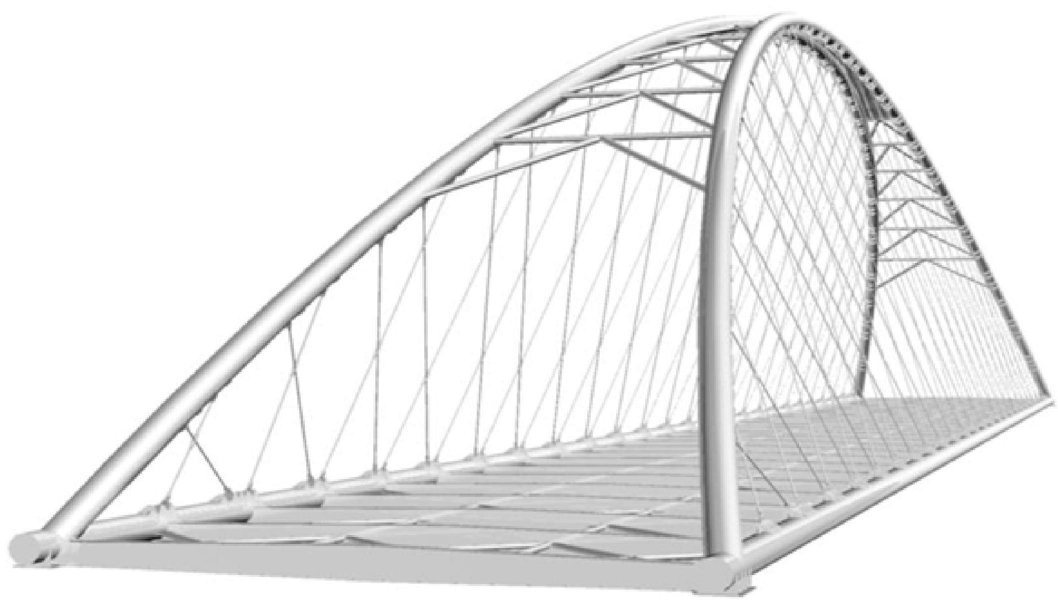

Figure 6: 3D view of the NA130.

The deck, made of reinforced concrete, has a thickness of 30 cm including the *predalles* slab used as formwork. The total cross section is 14 m wide with the center section of 10.50 m road dedicated to the platform, including two lanes of 3.75 m, lateral lanes of 1.50 m, side areas of 0.75 m (to accommodate the barrier guard rails). This floor serves as a support plan for the road and is usually made of cast in place concrete. It has the dual task of transferring, transversely to the main structure, the vertical road loads and collaborate with the main structure in the transverse direction. The slab is cast in place using self-supporting scaffolds. Strands are realized with tension rod, with varied inclination according to the geometrical pre-design optimization performed. Bridge substructure is made up of abutment, carrying loads to the piles. Foundations rest on piles of 100 cm of diameter, 20 m long, resting on a compact sandy gravel. The reinforced concrete basement has a constant height of 2.4m.

Before reaching the proposed structural design, parametrical studies have been performed in order to optimize the material grade, the structural shape (including hangers geometry), structural detailing cost (welding/bolting). The structural steel members are designed mainly nearly the 75% of the design stress vs. all loading combinations. In this particular case [3], the strength can be fully utilized and the cost of material is generally lowered as the strength is increased. However, the present study doesn't take into consideration the fabrication and erection cost, that could have a particular influence in the structure realization. Other studies have been focused on deck deformation, defining an optimized r.c. deck shape (see figure 9). Finally, detailed investigations for bridge structural details, aiming at revealing stress concentrations, have been performed with separate sub-models of the structure: one of the most stressed detail is represented by the outer strand hangers; for this reason, sub-fem models have been implemented in order to investigate peak stress regions, and optimal shape definition for critical details. A synthesis of this study has been reported in the following figures.

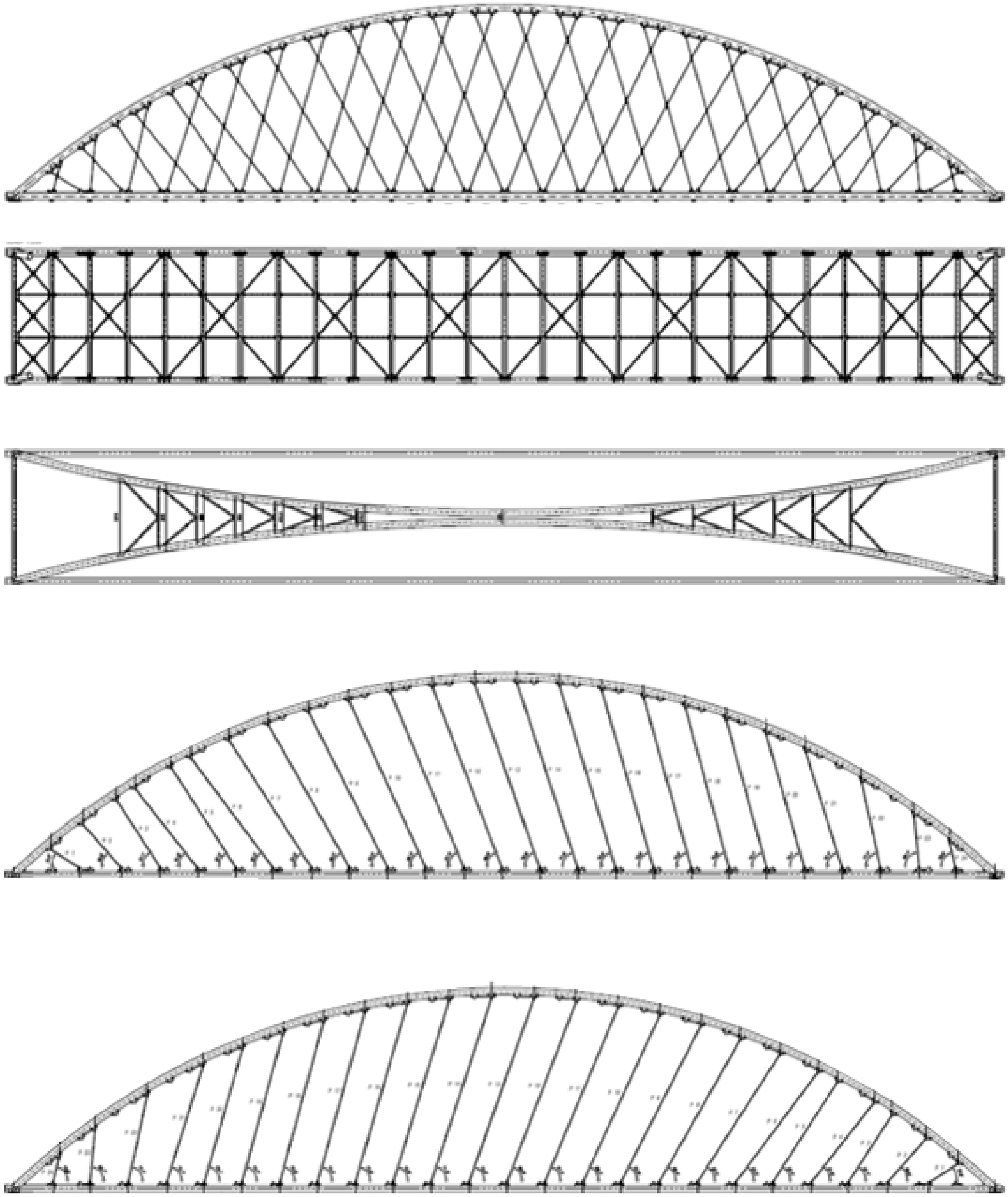

Figure 7: Lateral view of the arch and strand geometry.

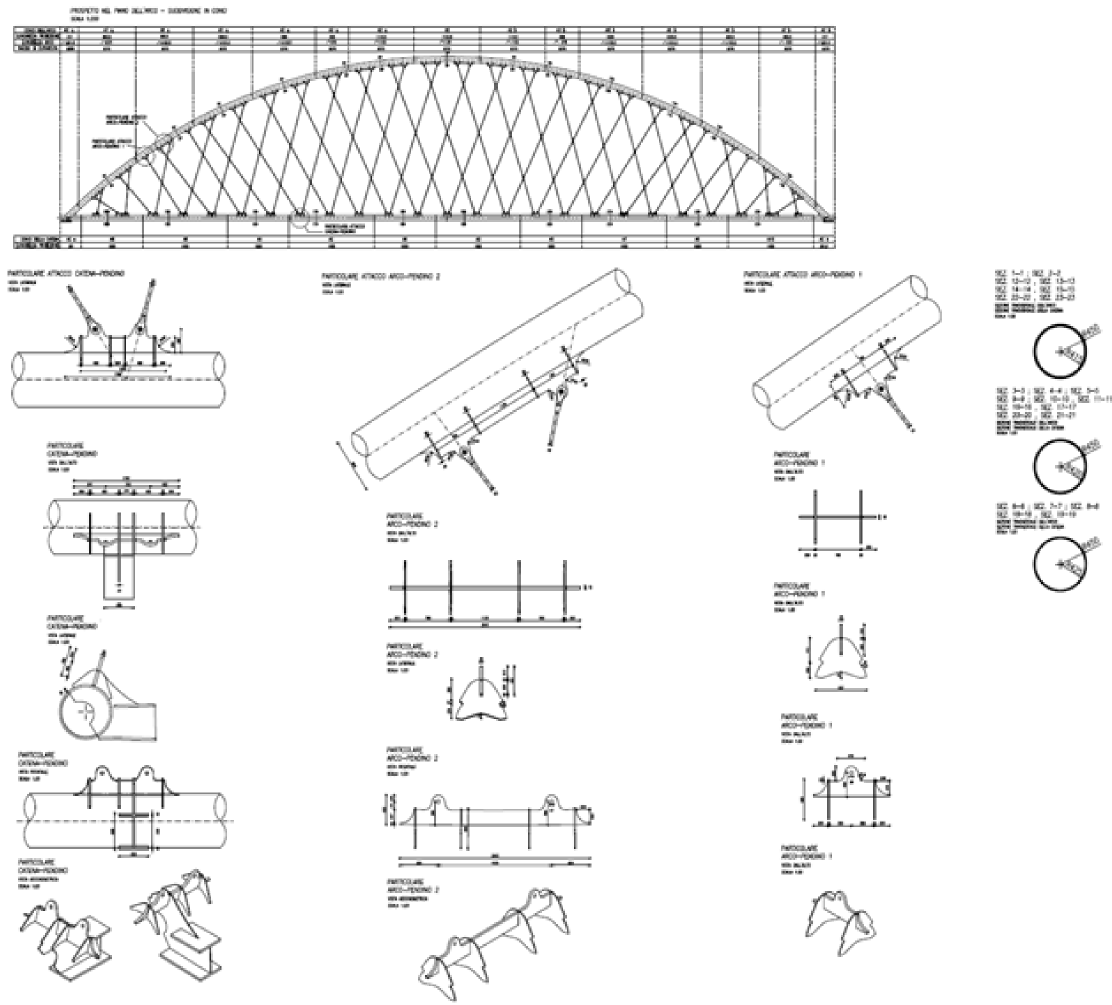

Figure 8: Strand hangers and anchorages details.

The geometry of one of these detail is reported in figure 10, while in figures 11-12 it could be seen the detail in the context of the principle structure and the stress levels highlighted by the analysis; a full penetration welded connection is verified at the ultimate limit state, in accordance with the requirements of UNI EN 1993-1-8, section 4.7.1, according to EN-1993-1-12 principles.

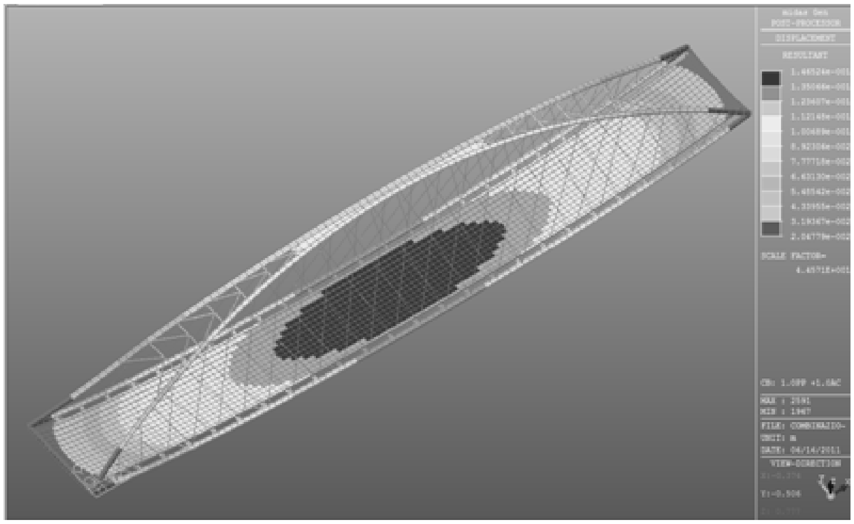

Figure 9: Displacement under vertical loads of the deck .

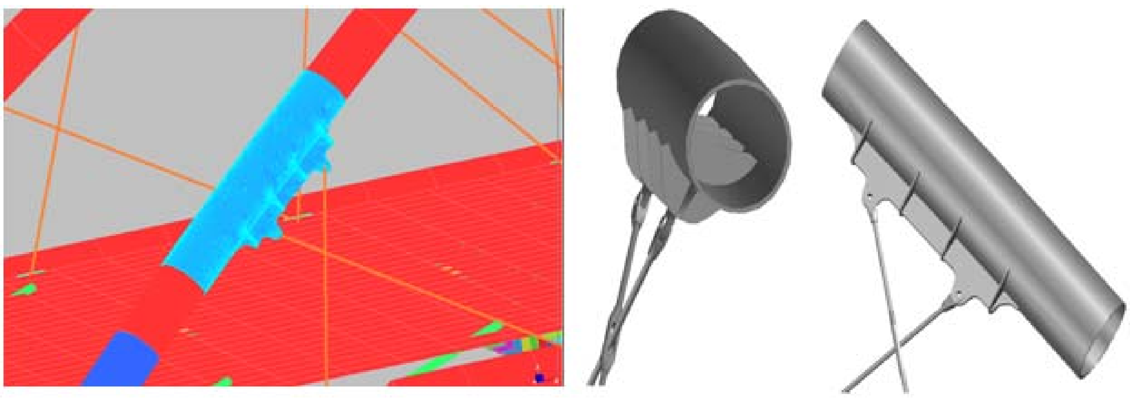

Figure 10: Outer hangers FEM detail.

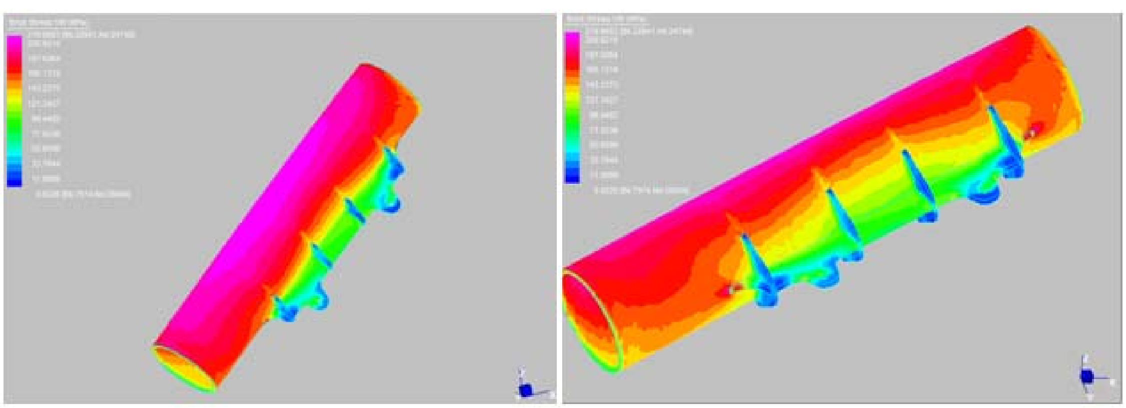

Figure 11:Outer hanger Fem detail, stress analysis.

A detailed investigation, that is recurrent in these bridge types, involved the fatigue verification of strands and hangers structures to be designed on the lower arch: particularly in this last position could be found peak stresses related to cyclic loadings. The geometry of one of these detail is reported in figure 12, while in figure 13 it could be seen the detail in the context of the principle structure. In figure 14 are reported the stress levels highlighted by the analysis; also in this case a full penetration welded connection is verified at the fatigue serviceability limit state according to EN 1993-1-9 verification procedure.

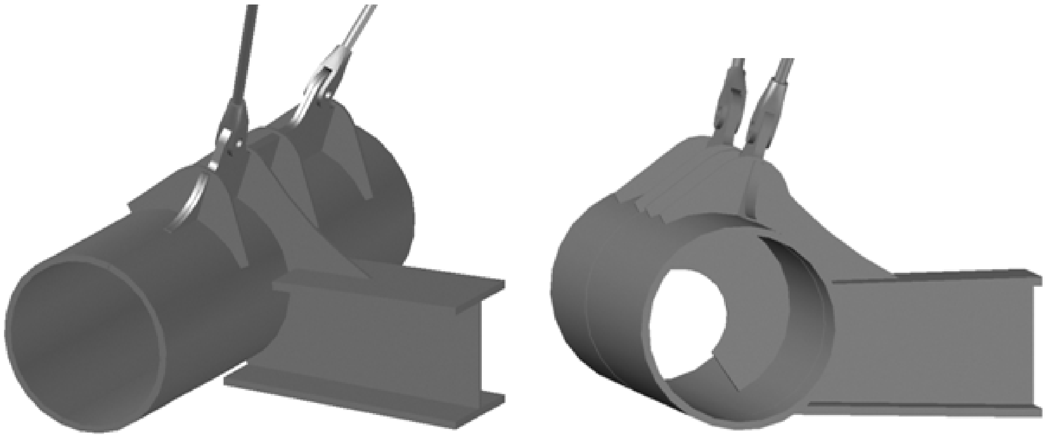

Figure 12:Recurrent hanging detail on the lower chord.

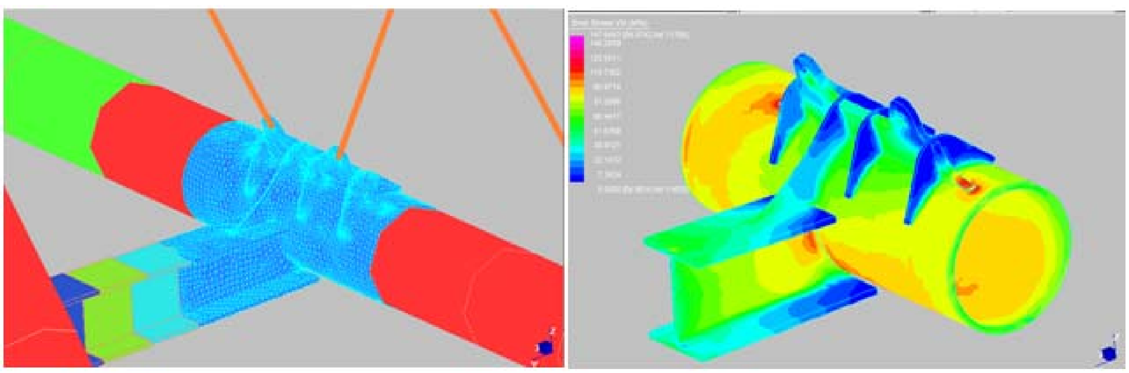

Figure 13: Recurrent hanging detail on the lower chord: FE- model and analysis.

Similarly to this last verification, a detailed investigation has been carried out for the arch to chord detail, also in structural part peak stresses could be avoided by detailed FEM analysis and structural shape optimization: some insights on this part of the structural design of the NA130 are reported in the following figure 14.

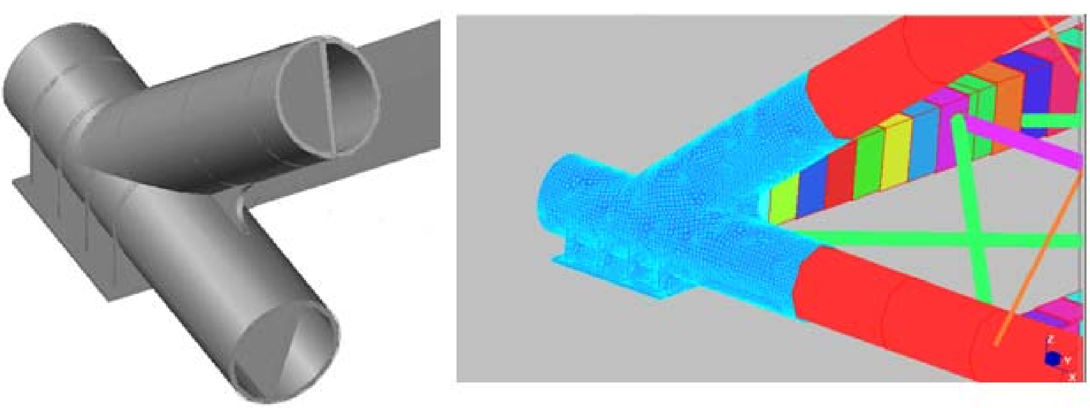

Figure 14: Arch to chord shape and FE-model.

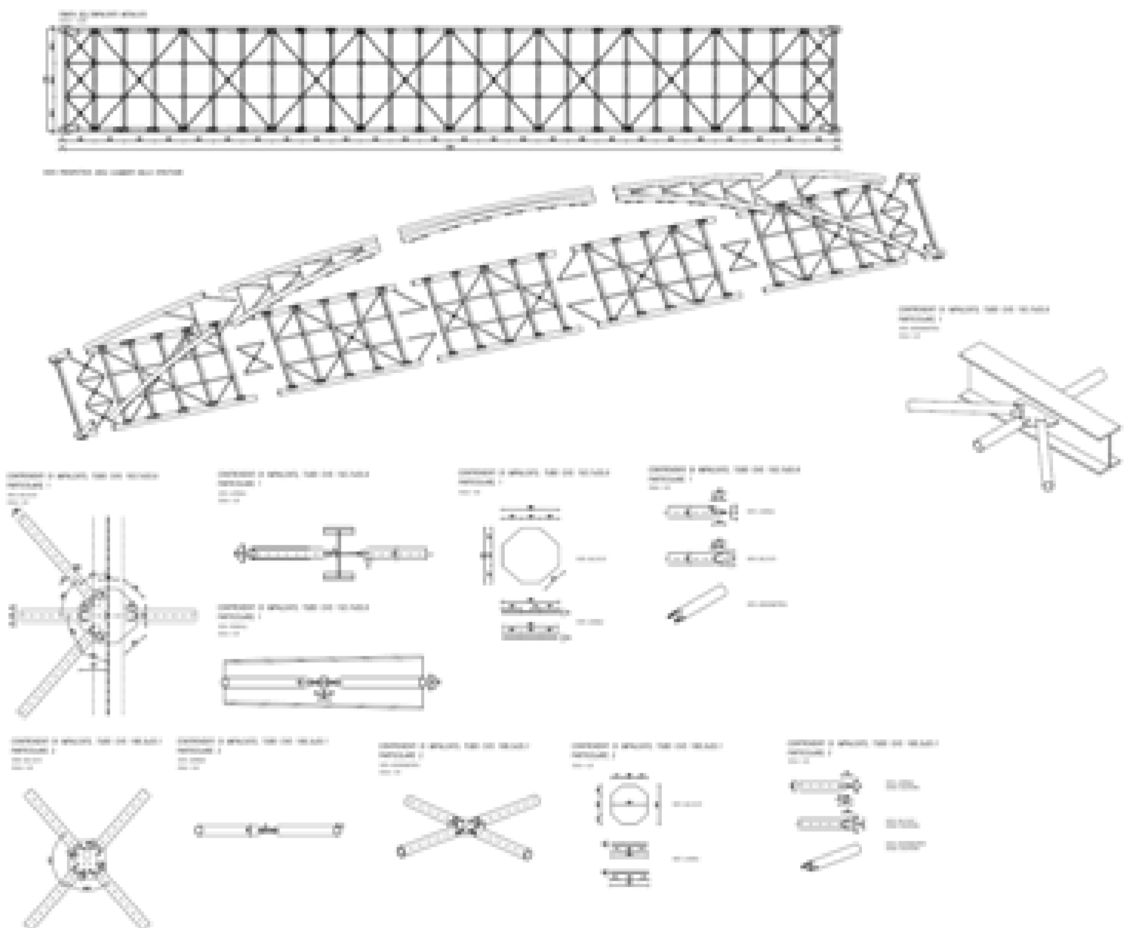

Figure 15:NA130 construction scheme.

Finally construction phases have been studied: according to this investigation, the arch will be realized dividing its shape into five parts, and the same substructures will be realized also for the deck; finally, only a structural combination will have to be realized on-site (see figure 15).

Conclusion

HSS are introduced in this paper, dealing with HSS products, European code specifications, design and research applications. The economical and sustainable aspects, together with practical insights on the design issues related to HSS applications in the bridge field are presented. As a result, new code requirements and design specifications are needed, in order to drive this construction market to other advanced steel materials, particularly in relation with AHSS, that will be the future of the steel construction global applications. Future studies and applications will be dedicated to higher HSS applications.

Acknowledgments

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