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The design approach of a prestressed concrete bridge constructed in 1950s in Italy

El enfoque de diseño de un puente de hormigón pretensado construido en los años 50 en Italia

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ABSTRACT

In years 1950 the first bridges realized with the emerging technique of Prestressed Concrete (PC) were designed and constructed in Italy. In this paper the design of San Nicola bridge erected in Benevento (Italy) and designed by Riccardo Morandi in 1952-1955 is presented in order to analyse its conceptual design. The original design has been examined evidencing a careful process of optimization by adopting an innovative method of construction with precasted segments. The influence of some choices in geometry, static scheme, prestressing procedure on the structural response of the structure are discussed also by simple examples.

KEYWORDS: Conceptual design; PC bridge; durability.

RESUMEN

En los años 50 se diseñaron y construyeron en Italia los primeros puentes realizados con la técnica emergente del hormigón pretensado (PC). En este trabajo se presenta el diseño del puente de San Nicola levantado en Benevento (Italia) y diseñado por Riccardo Morandi en 1952-1955 con el fin de analizar su diseño conceptual. Se ha examinado el diseño original evidenciando un cuidadoso proceso de optimización mediante la adopción de un innovador método de construcción con dovelas prefabricadas. La importancia de algunas decisiones geométricas, el esquema estático y el procedimiento de pretensado en la respuesta estructural de la estructura se comentan también mediante ejemplos sencillos.

PALABRAS CLAVE: Diseño conceptual; puente PC; durabilidad.

1.
INTRODUTION

The conceptual design of a structure is the preliminary and critical step of design during which essential features of construction take shape to optimize performance. The design process must be based on the fundamental principles of the structural engineering, boundary conditions and functionality required to the structure. Over the years, concepts about design have been certainly developed [1,2] and consolidated through great designers' activities that remain alive by means of structures built. It is therefore vital to screen the projects in the past to understand the conceptual path to design the struc-

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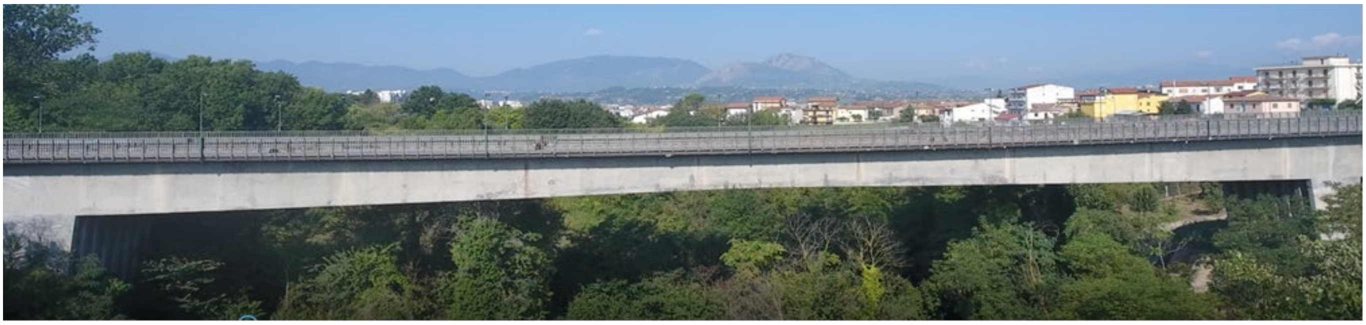

Figure 1. Current lateral view of San Nicola Bridge.

Figure 2. Transversal and frontal view of the pier.

ture, especially when the lifespan of construction confirmed its performance [3].

In this paper it is examined the design of the bridge San Nicola in Benevento (Italy) developed by Riccardo Morandi in 1950s [4]. Although this bridge is not especially known and important among the bridges designed by Morandi, it represents a bold and innovative design at the time putting into practice several choices aimed at the structural performance optimization.

The San Nicola bridge is a prestressed concrete cantilever bridge whose design involves a portal frame with two cantilevers and piers hinged at the basis. The construction technique was cutting-edge for its time and combined with the optimization of the shape was aimed to reduce stresses into the structure during both the construction and the serviceability life. The curved shape was common in the past [3,5] and the review of specific design choices should rise no doubts whatsoever about the advantages of prestressed concrete and segmental construction. Currently this type of static scheme is still used although provided with more innovative techniques such as seismic bearings [6].

A detailed examination of designer's choices for San Nicola Bridge and its effect on the performance of the structure are of great interest, pointing out how the basic principles are still valid. The proposed analysis deals with three main aspects: structure geometry, static scheme, prestressing.

2.
DESCRIPTION OF THE BRIDGE

The deck of San Nicola bridge is made of prestressed concrete cast in site with piers and foundations made of reinforced concrete. The design involves a portal frame composed by one main span 80.0 m long and two cantilevers of 20.0 m long as shown in figure 1.

The bridge deck is supported by two piers 9.40 m high and linked to the foundations underneath by hinges made of steel rebars. Each pier, as shown in figure 2, was realized by eight columns of rectangular section, 40.0 cm thick and variable width from 1.50 m at the base to 4.00 m at the top, that are transversally connected at the base and top by a transverse beam.

The foundations also act as abutments. The deck shows varying-depth through the spans (beam with curved intrados), which characterize an approximately linear shape giving also a beneficial arch effect. The depth of the deck cross section varies from a maximum of 3.60 m at the pier supports, to a minimum of 1.60 m at the ends of cantilevers and 2.70 m at the midspan. The deck consists of four prestressed box-girders, whose webs vary in thickness, from a minimum of 13 cm at the midspan, to a maximum of 30 cm at the supports. The width of the upper slab is 9.00 m and consists of two traffic lanes, 7.00 m width, and two sidewalks 1.00 m width each one. Also the thickness of the upper and bottom slabs is variable.

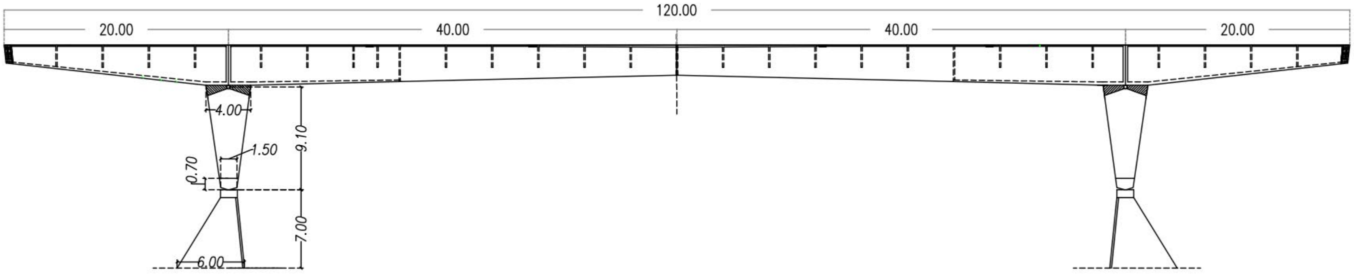

Figure 3. Longitudinal scheme of the bridge.

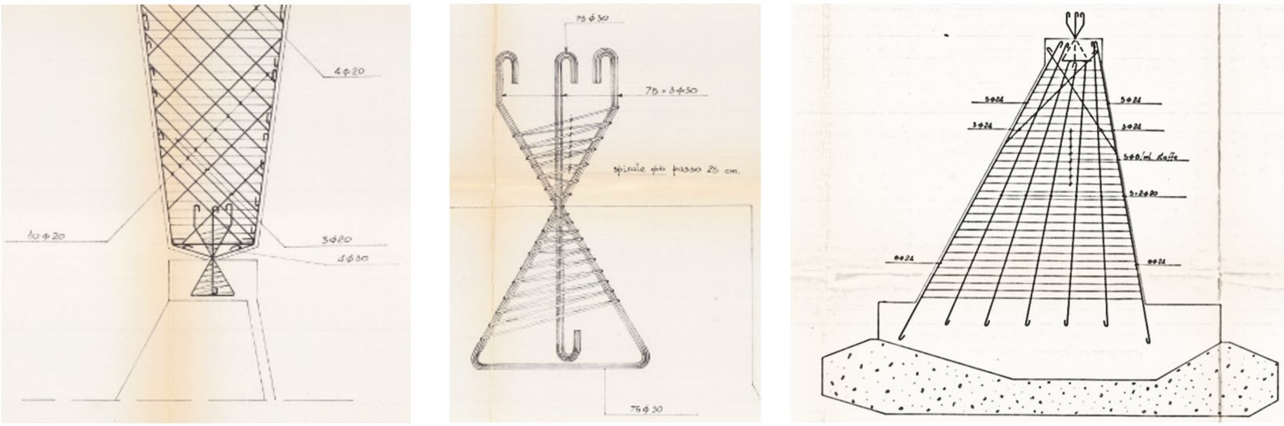

Figure 4. Details of the hinge at the column base and foundation.

The deck is characterized by internal tendons, symmetrical about midspan. The prestressing steel cables are composed of 27 aligned wires with diameter of 5 mm and were placed along a straight line in the top slab where the bending moment shows negative values and in the bottom slab in the midspan, but also curved cables were installed along the entire bridge. The anchorage is achieved by means of steel plates. The materials used were concrete with compressive strength of 450 kg/cm2 (44 MPa), steel for reinforcing bars with yield strength of 2300 kg/cm^2 (225 MPa) and prestressed steel with minimum tensile strength of 1 800 kg/cm^2 (176 MPa). The piers are reinforced with TOR (Toristeg Steel Corporation of Luxemburg) steel bars.

The construction technique was cutting-edge for its time. The precast reinforced concrete segments of the deck were produced on site, by setting up steel ducts for installation of tendons. Then the segments were raised on "Innocenti" pipe centering and then jointed with cast-in place concrete of about 15 cm thickness. The deck was prestressed when was simple supported on temporary restraints made with steel cylinders located on the top of the piers, then it was connected to the piers realizing a not determined static scheme.

Nowadays the same type of beam with curved intrados of San Nicola bridge is still adopted since it magnifies the aesthetic [7,8] and the performance of the structure, but usually also the external spans are supported on abutments. Furthermore, the construction by segments is currently used but through the technique of balanced cantilever using cranes or launching systems to realize the hammer with the pier and two cantilevered decks and then connecting the midspan. Various problems due to the intermediate conditions [9] or new constructional techniques [10] are of research interest.

3.
THE DESIGN OF GEOMETRY AND STATIC SCHEME

The San Nicola bridge is located out of the city centre of Benevento and was designed to connect two parts of the city crossing the creek San Nicola that goes through a valley with instable hillsides. Therefore, the first step of the design was the definition of the solution to absolve the aim of connecting the road but, considering the fragility of the hillsides, the piers were founded on the banks of the creek and the deck was developed symmetrically with a span and two cantilevers. However, the choice of an isostatic beam simple supported by the piers would be too onerous in terms of stresses due to the traffic load, therefore the designers identified two steps of realization. The first one was the simply supported beam to apply the prestressing and the second one was a frame scheme integrating the joint between the deck and piers as shown in figure 3. The two cantilevers solved the problem of the low bearing capacity of the hillsides but also optimized the distribution of bending moments along the deck reducing the sagging moment in the span. The piers were hinged at the base to avoid bending moments on the foundation that have to also contain the thrust; in figure 4 the detail of the hinge at the column base is shown.

In figure 5 it is possible to observe the temporary supports of the deck on the piers that were realised with steel cylinders to apply the prestressing on a static determined scheme avoiding reaction forces due to this technique. The solidarization between the deck and the piers was realized casting concrete in the gap surrounding the temporary steel supports through a hole in the caisson.

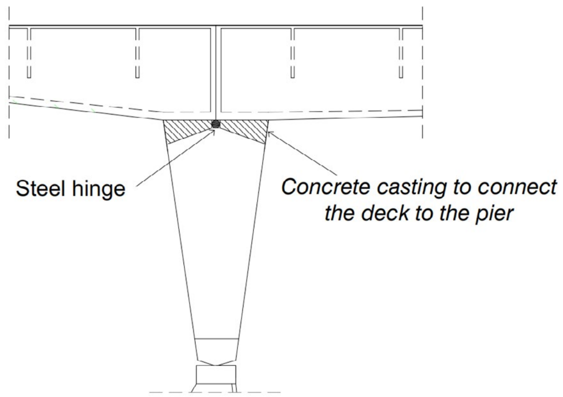

Figure 5. Detail of temporary support made of steel cylinder for applying prestressing.

During the time the design of the static scheme with the two cantilevers for avoiding the problems of the instable hillsides resulted a winning choice. In fact the flood of 2015 in Benevento caused the landslide of the slopes without damaging the bridge. After that sustaining works were realized by gabions and armed lands, as shown in figure 6.

4.
THE DECK

The optimization of the static scheme was pursued also adopting a section of the deck made of caissons with thin thickness and a variable height, as shown in figure 7.

In particular, the height and the thickness of the multicellular caisson is variable along the deck as the bending moment assumes its maximum value at the column joints but reduces at the midspan and becomes zero at the end of the cantilevers. The reduction of the design moment along the deck allows to reduce the height of the section and its weight, optimizing the shape according to the response of the structure. Clearly

Figure 6. The landslide of the slope in 2015 and the armed lands behind the pier.

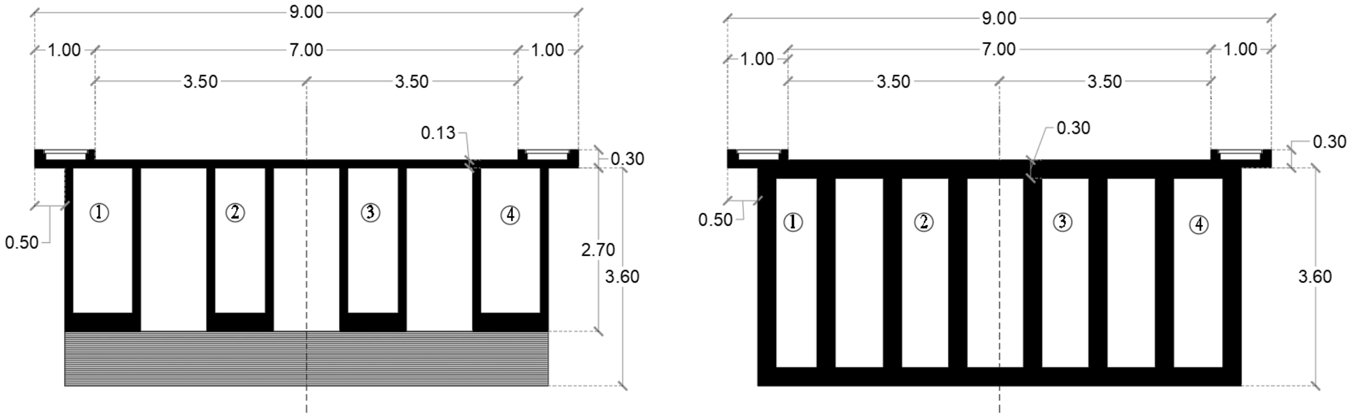

Figure 7. Cross sections of caissons at the midspan (left) and the supports (right).

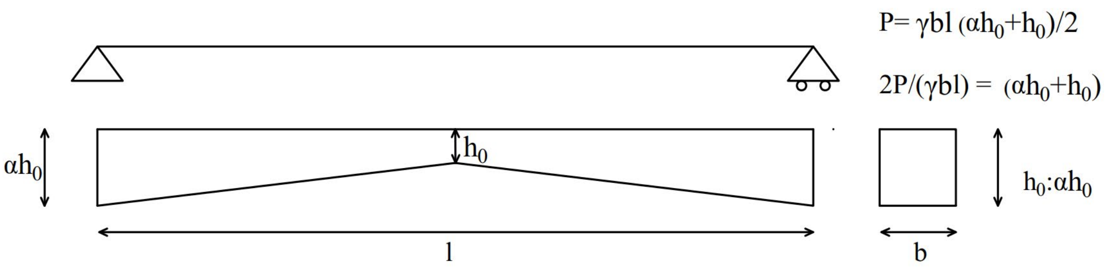

Figure 8. Simple supported beam with rectangular section and variable height under self weight.

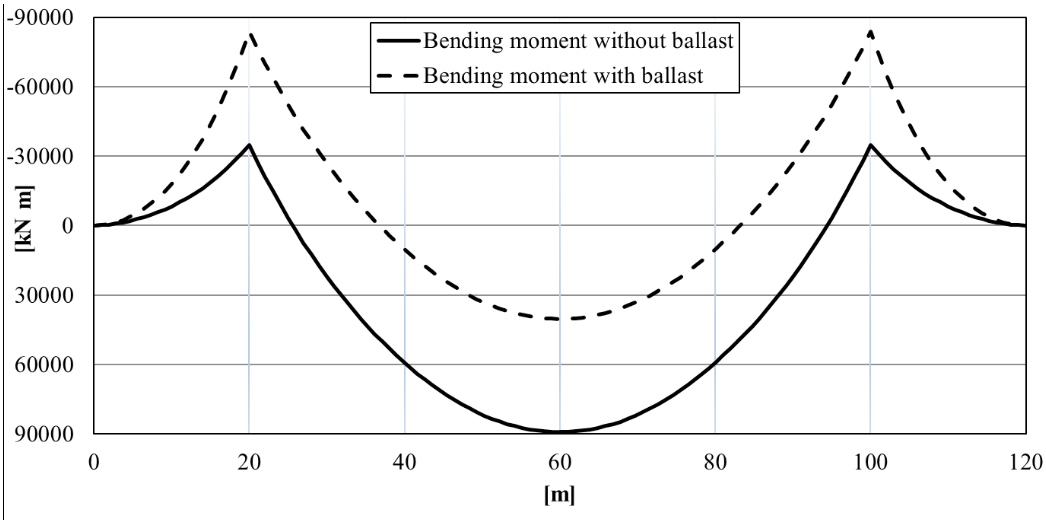

Figure 9. Bending moment along San Nicola bridge under self weight in case of simple supported scheme.

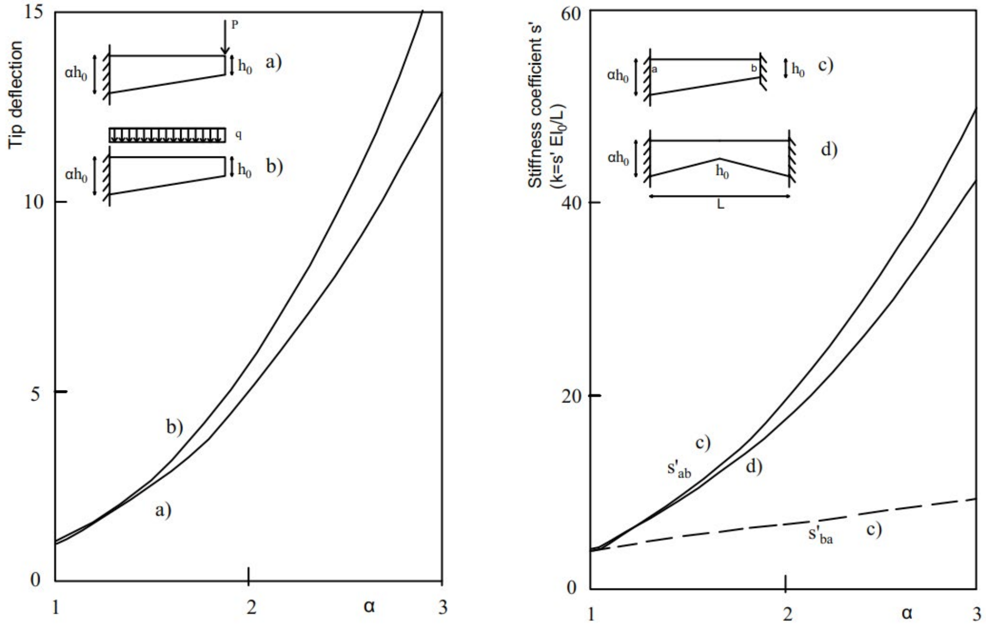

Figure 10. Taper effects on deflection and bending stiffness [11]: cantilever under tip loading (left), fixed-fixed tapered beam for stiffness of both ends a and b (s'ab and s'ba) (right).

minimum dimensions of the thickness were considered but sufficient to introduce the ducts for the cables, but the thickness of the webs of the caissons has to satisfy also the shear stresses, therefore, are 13 cm thick at the midspan and 30 cm at the supports.

The upper slab shows a variable thickness too, from a minimum of 13 cm at the midspan (sagging moment), to a maximum of 20 cm at the supports (hogging moment). The bottom thickness of the four caissons varies from a minimum of 20 cm at the supports, to a maximum of 30 cm at the midspan where many cables have to be located; furthermore, the caissons are connected by the bottom slab close to the piers and in the cantilevers, where the bottom slab is in compression. This last condition allowed to fill the caissons of the cantilevers with gravel and sand to balance hogging and sagging moments along the entire deck, reducing the positive moment at the midspan. This solution allowed to the designer a further reduction of the stresses along the span, making possible a further optimization of the section dimensions.

An example of a simple supported beam with length l=80 m is proposed, as shown in figure 8, in order to better understand the benefit of adopting a section with a variable height. Assuming a rectangular section when the height varies between αh_0 = 3.6 m (α=1.33) at the supports and h_0 = 2.7 m in the midspan, the maximum sagging moment due to the self weight (unit weight γ) reduces of 5% assuming the tapered shape respect to a beam with the same weight P but having a constant height of 3.15 m.

Furthermore, for the San Nicola bridge the cantilevers could reduce the sagging moment in the midspan of about

Figure 11. From the left: anchorage of two cables in groups of 3 wires, real picture *in-situ*, patent M1 and patent M4.

Figure 12. From the left: duct filled with mortar, duct not filled with mortar and degradation of the deck due to water.

30%. But the designer wanted an higher reduction of the sagging moment due to the permanent loads in order to have an adequate resistance for the traffic load even though a reduced height of the section in the midspan, therefore he added sand in the caissons of the cantilevers. This dead load was defined imposing a prefixed value of the maximum positive moment in the design; in particular, it was reduced of 55%, moving an increment of 58% of the negative moment at the supports.

Really an optimization was made by Morandi between the shape of the cantilever that could give a prefixed moment at the supports to reduce the moment in the midspan making the longitudinal shape of the deck perfectly adequate to the moment shape as shown in figure 9, with a reduction of material costs and an higher lateral stability of the deck [11].

Also the piers were tailored as the moment trend, that is zero at the base hinge and maximum at the top. The variable section influences also the stiffness of the deck. In fact, the deflection of a tapered rectangular beam could be reduced by over a factor of 12 when the ratio of height of ends of the beam α is 3, as shown in figure 10 (a-b); the relation is of exponential form. Similarly, the end rotational stiffness of a fixed-fixed beam can be increased from 4EI/L to over 48EI/L for fixed-fixed tapered beam, shown in figure 10 (c-d) [11]. In case of Morandi bridge the variability of the deck and piers section was designed to obtain approximately the same flexural stiffness for the deck and the pier; in particular the distribution factors of the moments at the frame joint are 0.60 and 0.40 respectively for the deck and the pier.

Furthermore, the variable height of the deck activates an arch effect that contributes to carry the vertical loads by compression forces [11]. The value of the axial load in compression due to the self weight is 594.5 t (5830 kN) at the support and 436 t (4275 kN) at the midspan, that give respectively a stress of 32% and 19% of the design strength of concrete assumed as 270 kg/cm^2 (27 MPa). Again, the shape of the deck gives a beneficial effect for the performance of the bridge.

5.

DESIGN OF PRESTRESSING SYSTEM

The construction procedure was an important aspect of the conceptual design and was defined to allow the prestressing of the entire deck also with continuous cables [12,13]. Various techniques were developed to realize bridges in 50' [14]; for the San Nicola bridge the caissons of the deck were realized in pieces 2 m long lifted on the provisional "Innocenti" system and jointed with concrete casting that filled approximatively 15 cm of gap. In this gap the ducts of the pieces were connected with steel sleeves made with thin plates. The

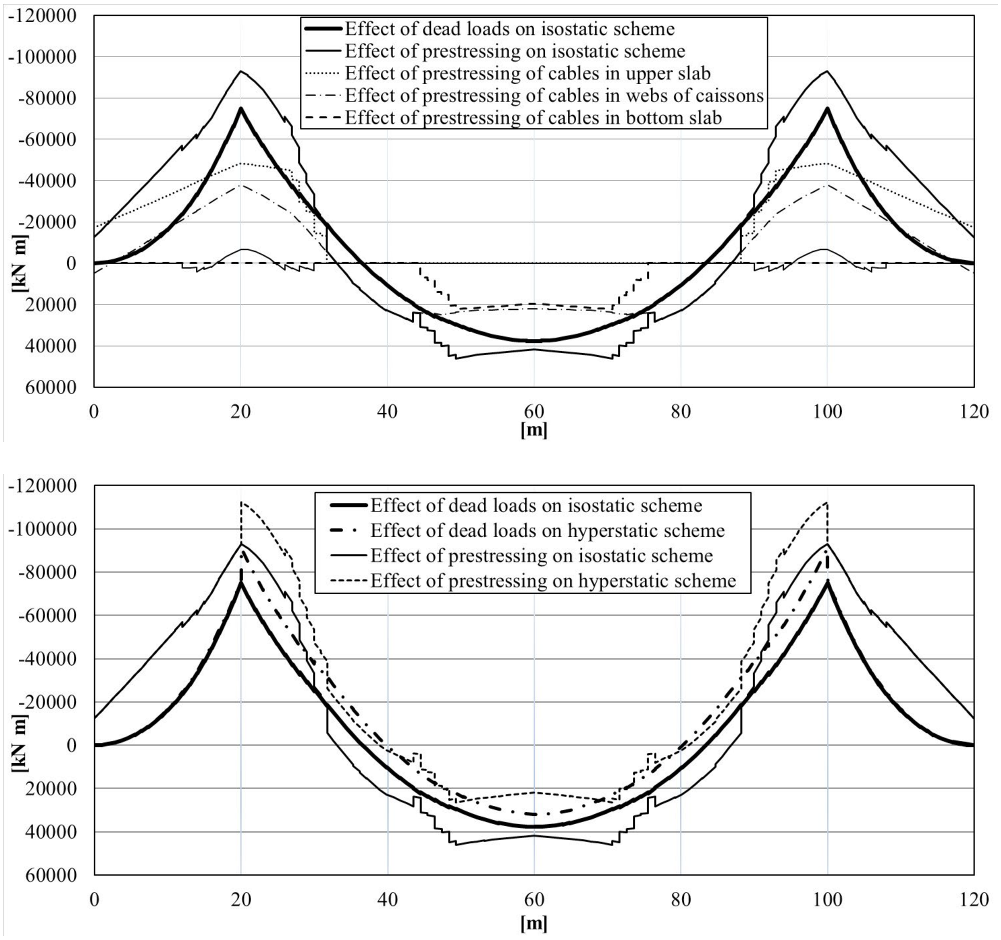

Figure 13. Diagrams of bending moment along the deck, due to dead load and prestressing.

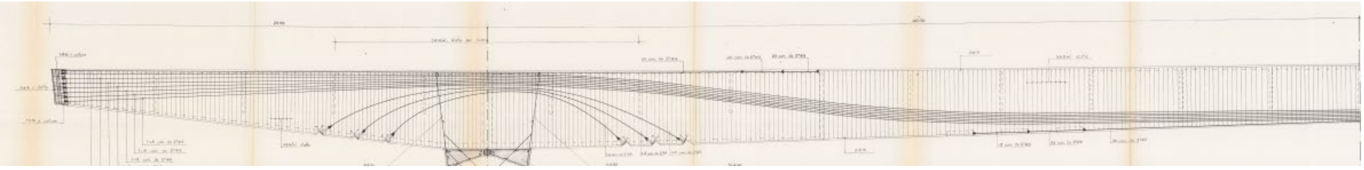

Figure 14. Original drawing with the prestressing cables.

total number of cables is 252, each one made of 27 wires of 5 mm diameter. The wires were introduced in the ducts and put in tension in groups of 3. The anchorage system is a patent of Morandi and was realized by a steel plate 5 mm thick with dimensions 40x25 cm. Each cable was fixed at the anchorage in 9 points (3 wires for point) through bushings [13] of diameter 3.4 cm, and each plate anchors 2 cables, as shown in figure 11 (left).

The tensioning of the cables was applied by both ends using a set up of the Morandi patent that allowed to block and unblock the cables for recovering the stress losses; after the prestressing procedure the anchorage plates were covered with a finishing of concrete.

In the design documents there are not specific informations about the set up used for tensioning the cables but considering the type of anchorage detected during a surveys campaign and the literature on Morandi work, the patent M4 was identified and it is reported in figure 11 with the patent M1.

The cables were lubricated with Stauffer grease before prestressing owing to their significant length and every 40.0 m holes were predisposed for any future lubricant injections and grout injections after prestressing.

The tests *in situ* evidenced the good condition of the tendons, as shown in figure 12, both in case of duct completely filled and not filled with mortar, because the air in the duct does not allow the development of corrosion. Corrosion was detected in the zone of the deck where stagnation of water occurs due to a bad disposal of water, as shown in figure 12 in the right.

The designer chose to realize the structure in two steps in order to apply the prestressing to a provisional determined static scheme. In fact, in the first stage the deck was support-

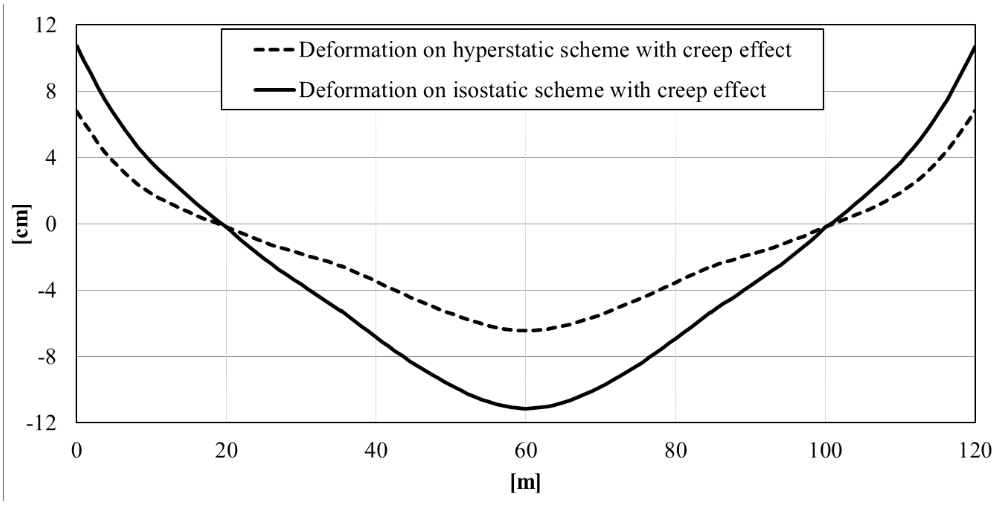

Figure 15. Theoretical deformation with creep effect under dead loads.

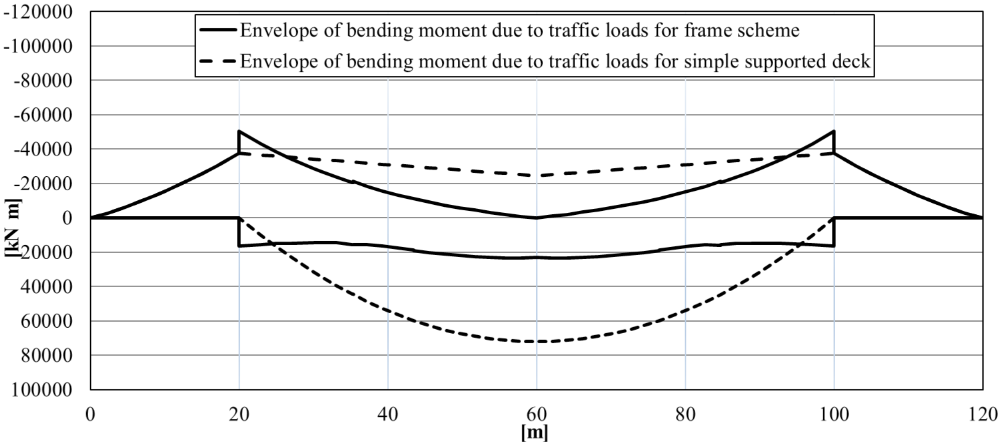

Figure 16. Bending moment due to the traffic load for the frame scheme and the simple supported beam.

ed by steel cylindrical hinges on the two piers while in the second stage, after the prestressing, concrete was cast into the gap surrounding the temporary steel supports as shown in figure 5. Prestressing a determined static scheme allowed to prevent reactions which are forces and bending moment on piers and also bending moment and shear in the deck, albeit Morandi thought that prestressing could be conveniently applied to a hyperstatic structure with suitable discernments [15].

In particular, due to the prestressing on the hyperstatic scheme the horizontal force rising on piers would have been of 176 t (1726 kN) under dead loads, which is about 43% of the thrust due to traffic loads of that time.

In figure 13 the diagrams of bending moment due to dead loads and the prestressed cables are reported with the same sign to better compare them, but the effect of prestressing has opposite sign; the prestressing on the static scheme equates and annul the moment due to the dead load. The placement of the cables has been carefully designed to optimize the effectiveness and follows the line of the moment due to the dead loads. Straight cables in number of 60 for each side were placed in the upper slab, lying from the tip of the cantilevers to 12 m inside the main span, 36 straight cables were placed in the bottom slab in the midspan and 56 curved cables were placed along the bridge, 7 in each web of the caissons. It is possible to observe the position of the cables in figure 14 from the original drawing.

Moreover, on each support 20 curved cables at three different heights were placed. Three in each external webs for a total of 12, and 2 in each internal webs for a total of 8. The straight cables, in groups of 20 in the upper slab and 12 in the bottom one, were anchored in offset sections of 2 m to get both an optimization and the possibility to place the steel anchor plates in the thin slabs.

The high number of cables made of many wires and anchored in different sections give a low probability of a contemporary loss of the entire prestressing avoiding a brittle and sudden failure of the bridge.

The choice to have a hyperstatic structure after the prestressing was dictated not only to reduce the stresses due to traffic, but also to reduce the creep deformations that develop over time due to permanent loads. In fact, the deflection under permanent loads can be evaluated and compared for the isostatic and the hyperstatic scheme, considering the effect of the post-installed restraints and the segmental procedure [16]. The following simply assumptions, unverifiable nowadays, can be assumed:

- Neglecting the effect of the assembling of segments with grout and considering the construction of the deck in one step;
- removal of "Innocenti" system after 2 months by casting concrete and prestressing operations;
- the creep factor is assumed ϕ=2.5;
- the prestressing loss is neglected to evidence only the effect of the static scheme;
- the dead load also with ballast is considered.

The results are shown in figure 15. The effect of the final restraints is important also for the long time deflection and gives a reduction of 40%, respect to the isostatic one.

The bending moment due to traffic load results 60% higher at the midspan and 22% lower at the supports considering the simple supported beam instead of the frame scheme. Therefore, the utility of the final restraints is confirmed. In figure 16 the comparison between the envelope of bending moment due only to the traffic load, according to the Italian Code NTC2018 [17], for the frame scheme and the simple supported deck is reported.

Finally it is worth noticing that the maximum bending moment due to the traffic load is approximately 44% of the one due to the self weight; therefore the safety factors for the action of the self weight give a consistent reserve of safety for the increment of the traffic load as currently occurs. Conversely, a lighter structure would be more vulnerable respect to the live loads.

6.
CONCLUSION

The analysis of the design approach by Morandi adopted for the San Nicola bridge highlights the importance of a global view involving the construction technique, transitional conditions during its construction and serviceability state over the years. Studies and ongoing research about optimization in the shape, pattern of prestressing and static scheme provide a solution that suits the environmental context into which it is built and the economic process. It is also clear the aesthetic that seeks to communicate through its shape the static behaviour of the structure providing the reading of distribution of the dead load and stresses paths. The cantilevers reduce the sagging moment in the midspan of about 30%, but by adding ballast inside the caissons the bending moment due to dead load was reduced of 55%, moving an increment of 58% of the negative moment at the supports. This result is an optimization using the variable height of the deck with the greatest value at the supports. The variable longitudinal shape activates an arch effect that contributes to carry the vertical loads by axial compression forces.

The laborious and continuous optimization process of the shape and distribution of dead loads was supplemented with a detailed configuration of prestressing, accompanied by technical innovation through patents developed by the designer. The result is an efficient solution, since the cables act as restrain where the external stresses are greater, but at the same time it is provided with a redundancy due to the distribution of prestressing in a great number of cables, each one made up of significant number of wires. The last aspect to be mentioned is that in a so bold approach for that time, considering the technologies of realization and calculations only possible by means of simplified models, the designer chose thin thickness for the section making an important sign of full confidence in basic concepts proposed by the innovative technique of prestressing. Infact, if prestressing on the hyperstatic scheme, the horizontal force rising on piers would have been of 43% of the thrust due to traffic loads of that time.

The choice of the frame scheme affects the long time deflection and gives a reduction of 40%, respect to the isostatic one. Moreover, the bending moment due to traffic load results 60% lower at the midspan and 22% higher at the supports considering the frame scheme instead of simple supported beam. Therefore, the utility of the final restraints is confirmed.

After more than sixty years the bridge is in use and shows only degradation due to problems of maintenance confirming that a correct conceptual design really ensures the quality of the construction during the time.

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