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Procedia Manufacturing 44 (2020) 473–480

Procedia MANUFACTURING

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1st International Conference on Optimization-Driven Architectural Design (OPTARCH 2019)

Parametric Design: formal and structural connection for a pedestrian bridge in the archeological area of Roca Vecchia (IT)

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Abstract

The work done, lays the foundations for a design methodology that connects the formal and structural aspects of an architecture passing through the parametrization of geometric shapes.

To carry out the steps of the design method, the design of a steel pedestrian bridge was experimented.

The analysis of the structure made use of the AutoDesk Structural Analysis Robot calculation software; the geometry was parameterized using the AutoDesk Dynamo Studio software (Robot plug-in). The architectural design was carried out using the aforementioned software, managing to connect the formal and the structural part of the project, reaching a focus on the forms of architecture that directly influence the structural functionality.

The advantage in this type of design lies in being able to analyze a structure and assign different characteristics to it (from morphology to detail) in real time, managing to connect the project idea directly with a finished product.

Keywords: Structural Design, Structural Optimization, Parametric Design, Architectural Design

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10.1016/j.promfg.2020.02.268

1. Site Planning

The work produced focused on the architectural and structural planning of a cycle pedestrian bridge located within the archaeological area of Roca Vecchia, close to the Grotta della Poesia between Otranto and San Foca (Apulia, Italy).

The design hypothesis has been developed through the "computational design" by studying geometries and the consequent structural performances of the geometric shape that in this case they will refer to the characteristics of the arch. The archaeological area and the one belonging to the Grotta della Poesia are physically separated by a natural inlet that allows the Adriatic Sea to infiltrate between these two headlands (Fig.1), an area that lends itself perfectly to the connection through an infrastructure that becomes an important connecting point between two functions: the historical one and the bathing one (Fig. 1(a), (b)).

(a) (b)

Fig. 1. (a) Archaeological area and cave of the poetry; (b) Plan of the possible scenario for the Archaeological Park.

2. Structural Model

Starting from the material treated in order to design the infrastructure, it was possible to identify a structural model; Steel is the chosen material and is widely used for infrastructure such as bridges characterized by resistance to bending, to tensile stress and even compression [1].

The chosen basic structure of the model is the *curvilinear axis beam* which generates a circular arc that runs from one side to the other of the platform. The chosen shape allows to withstand high compression stresses and gives elegance to the arch ("bowstring arch scheme") (Fig.2) [2]. In this model, the deck beam is linked to the extreme points of the arch in order to form a structure that reminds one of a violin bow which is standing on the foundations in a continuous system with the arch. In this way, the horizontal thrust generated by the arch will be absorbed by the deck beam that will be stretched under the action of the thrust itself. This scheme generates a balanced body with horizontal forces to which only the foundation supports will be added. Actually, this model appears to be isostatic in the two dimensions, allowing even the realization of an elastic support in one of the two extremes of the arch, ensuring a free movement of the structure in order to dissipate the extensional effects of the thermal loads, loads that appear to be more intense in the presence of steel structures like this. Finally, the whole system makes it possible to prefabricate most of the main elements such as beams, connecting beams and cables of rod and ensures that the entire structural body can be assembled and disassembled in cases of need and maintenance of the work itself. The weight of the deck beam itself, plus the variable weights brought and provided by it, are transmitted to the arch through the cables of rod that tend to compress the arch further.

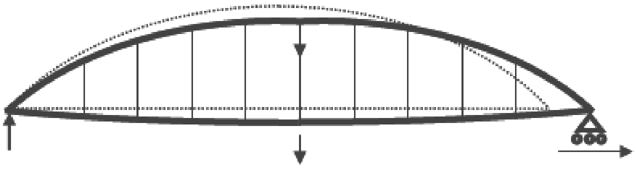


Fig. 2. Bowstring arch scheme.

Thus, the arch is compressed due to the variable load of the beam, the weight of the beam and its own weight. At the extreme points of the arch, which stand on the supports, a lateral thrust is evident, which tends to overturn the supports. These two horizontal thrusts, equal and opposite, tension the connecting beam that cushion the effects on the foundations. In conclusion, the model is statically balanced for vertical and horizontal actions. The foundation supports will guarantee an adequate resistance to vertical actions, while horizontal actions will be mainly absorbed by the deck beam. Three-dimensionally, the four supports at the ends of the two arches that form the structure also deny the displacement on the incoming and outgoing plane from the sheet so that the structure is balanced also for transversal actions such as wind or relatively minor earthquake.

3. Parameterization of geometries

The identification of geometries and proportions, which have determined the structure, were implemented through the use of the Dynamo Studio software [3]. The objective is therefore to establish the algebraic relations between the various elements in order to obtain results that are a function of these values previously imposed and on which all the others depend. The mathematical relations encountered here are basically referred to the theory of trigonometry (Fig. 3).

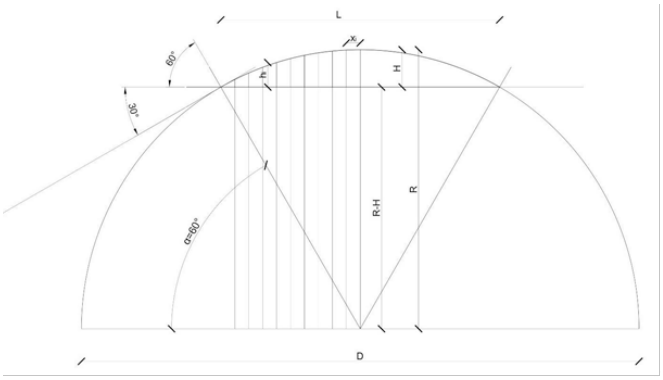


Fig. 3. Identification of the geometric parameters of the bridge structure.

What has been imposed on the design is the value referred to the angle that describes a rotation of the radius starting from a horizontal reference. This rotation of 60 degrees, indicated in the figure α, makes it possible to meet, on the circumference, the point from which the line representing the measurement of the deck supported by the cables of rod will be started, all properly mirrored on the vertical reference axis. In this way it was possible to maintain the length *L* of the deck, in parametric form, so that, once a value has been chosen, together with the imposition of the angle, it is possible to generate the main characteristics of the circumference to which the arch belongs, that is, coordinates of the center and radius. Finally, the measurements referring to the maximum height H, to the heights of the individual cables of rod and to the distances between them indicated with xi were made explicit.

In order to adapt the geometry of the structure to different contexts and dimensions, we proceeded through the digital parameterization of the three-dimensional geometry of the bridge through the use of the AutoDesk Dynamo Studio calculation software; the interface is very similar to the calculation programs, but its functions are more focused on the three-dimensional parametric design, from which it is also possible to obtain a 3D visualization of the geometric and structural results of what has been numerically entered in the software (input - output). In our case, one of the first steps was to define within the work space the points that give rise to a circular arch or, beginning, end and maximum height of the arch; these three parameters are variable thanks to a specific function that allows you to vary the distances between the points of the geometry itself.

The different cable lengths have been obtained through the Cartesian coordinates referred to the points of the circumference whose radius and Cartesian coordinates of the center are known:

$$x^2 + y^2 - 2ax - 2B_y + a^2 + B^2 - R^2 = 0 \tag{1}$$

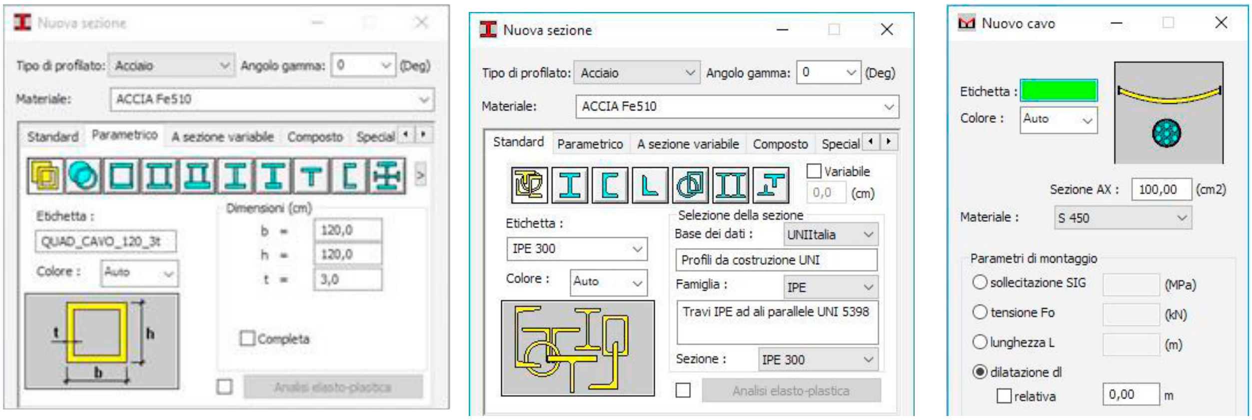
The whole, then, was made explicit by imposing the Y as the only variable (point belonging to the circumference) and using the desired abscissas, as equidistant points belonging to the beam platform representing the positions of the pulling cables. Connecting all the functions together in a cycle of mathematical expressions, with the complementary use of the so-called "sliders" to parametrically modify the dimensions of some main features of the geometry such as the length of the platform, the height of the arch and consequently, length and number of cables of rod, a three-dimensional geometry was obtained which readily adapts to the modification of all or even single dimensions of the elements that make up the structure. The Autodesk Dynamo software allowed the transposition of the obtained geometry and its related parametric changes with the help of the Structural Analysis Robot plug-in which will be used in the following steps to extrapolate the data regarding stresses, displacements, flexions and the support reactions.

4. Non-linear static analysis - Autodesk Structural Analysis

The most appropriate static analysis for this case, and for arcuate structures in general [4], is the non-linear one, which was performed through the calculation software already mentioned in this text: AutoDesk Structural Analysis Robot. The program has several functions designed to virtually simulate the actual real behavior of the structure modeled with other programs compatible with it. The first step was to create a three-dimensional model with the use of Dynamo Studio (schematized through the drawing of only lines and nodes edited in parametric form in order to be able to modify certain dimensions in real time). The 3D model thus obtained was exported in Robot in order to better define the model with the details; *Robot* works through lists of properties that are attributed to each element of the structure, be it a point, or a node, or a line. Once one of these two elements has been selected, it is possible to specify the fundamental characteristics for each, namely: material, modulus of elasticity, shape of the profile, thickness and area. The program also allows you to edit all the standard profiles on the market and automatically defines the properties that can still be modified by the user at any time. Like the profiles, all this can also be done for the constrains and for the loads, the databases thus created will be a source from which to draw in the attribution of the characteristics for each point or line of the model. The lists mentioned are shown below along with the specific properties chosen for the project in question.

4.1. Profile

The Robot software allows identifying the different elements of the structure based on their structural function, so it is possible to group the different elements into classes: Bars, Beams, Columns and Floors. Subsequently, the profiles of these elements were edited; the program allows you to create sections at will with all the features necessary to define them, such as materials, shape and thickness, so that you can attribute to each element the section associated with it (Fig.4.).



Tipo di profilato: Acciaio
Angolo gamma: 0 (Deg)
Materiale: ACCIA Fe510
Etichetta : QUAD_CAVO_120_3t
Colore : Auto
Dimensioni (cm)
b = 120,0
h = 120,0
t = 3,0
☐ Completa

Tipo di profilato: Acciaio
Angolo gamma: 0 (Deg)
Materiale: ACCIA Fe510
☐ Variabile 0,0 (cm)
Etichetta : IPE 300
Colore : Auto
Selezione della sezione
Base dei dati : UNIItalia
Profili da costruzione UNI
Famiglia : IPE
Travi IPE ad ali parallele UNI 5398
Sezione : IPE 300

Etichetta : 🟩
Colore : Auto
Sezione AX : 100,00 (cm2)
Materiale : S 450
Parametri di montaggio
○ sollecitazione SIG (MPa)
○ tensione Fo (kN)
○ lunghezza L (m)
● dilatazione dl
☐ relativa 0,00 m

Fig. 4. Identification and assignment of profiles for each individual part of the structure.

4.2. Constraints

The same procedure can be carried out for dates to be imposed on the nodes. The program allows you to edit a list of constraints to which it is possible to modify, add or subtract constraints, even imposing an elasticity where necessary. For the case concerned, we proceeded by analyzing both cases, that is with a support-support scheme and another support-cart-elastic, in order to explain the structural behavior differences. Moreover, the elastic constraint has been imposed with a value equal to the stiffness of the beam subtended to the arch obtained from the geometrical characteristics and from the material of the beam treated.

The KX value, which represents the extensional stiffness of the beam and together expresses the elasticity coefficient of the constraint, was calculated with the known formula [5]:

$$K = \frac{EA}{L} = \frac{20600MPa \cdot 71100mm^2}{100000mm} \cong 146{,}5 \cdot 10^5 \frac{kN}{m} \quad (2)$$

4.3. Loads

The program allows to establish the permanent and variable loads to be supported by the structure and which will then be inserted in the load combinations that are automatically generated by the program. The variable loads were chosen in accordance with the provisions of the NTCs, in the paragraph concerning bridges [6,7,8,9]. The load class most appropriate for this case is the number 5, associated to a value q equal to 5 kN/ m^2 for each lane that can be crossed. Once all these elements essential to the analysis have been defined, it is possible to calculate for all the parts of the structure their stresses, flexions, displacements and support reactions [6-8].

In order to obtain data that can be compared and with the aim of extrapolating the advantages or disadvantages deriving from different definitions of the structure scheme, we proceeded by analyzing the structural behaviors of two different models that stand out for the type of constraint imposed at one of the two supporting ends of the bridge.

The first case analyzed is the one obtained through the imposition of two (or four in the three dimensions), constraints that allow rotation and that constrain the displacements in all directions, or by applying the hinges (Fig. 5.(a)). The second one is the scheme that represents the structural model called “bowstring arch”, an isostatic scheme in which, on one of the two end hinges, a sliding carriage is imposed only and exclusively towards the axis of the deck whose elasticity it is expressed by the extensional stiffness of the deck that in this case will absorb part of the thrust generated by the arch and which will therefore undergo a greater stress in the direction of its axis, ie a traction (Fig. 5.(b)). This will allow a lightening of the foundations, which are exempted from compensating for the horizontal thrust and, moreover, will allow a minimum expansion of the deck beam element in order to dissipate possible heavy effects for the structure under the action of the thermal loads that in the structures completely made of steel, they can be of great intensity.

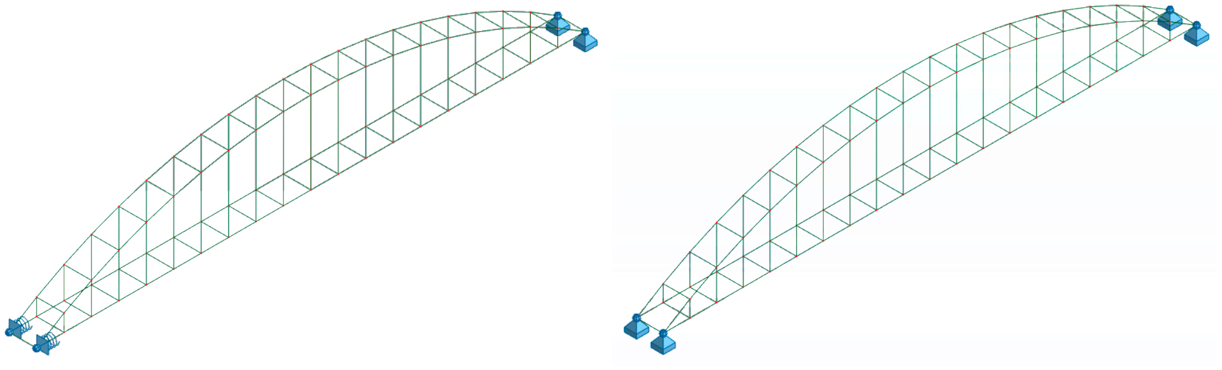

(a) (b)

Fig. 5. (a) Structural scheme with hinges only; (b) Structural scheme with hinges and elastic rockers.

5. Results

5.1. Hinge- Hinge combination and Elastic – Rocker combination

The results of the diagrams referring to the "*Hinge-Hinge*" (Fig. 6(a), (b), (c)) and "*Hinge – Elastic Rocker*"(Fig. 7.(a), (b), (c)) schemes are:

Table 1. Results diagrams hinge - hinge / hinge – elastic rocker combinations.

Combinations	Normal Stress (kN)	Bending Moment (kN)	Shear (kN)
Hinge - Hinge	6573,64	764	±199
Hinge – Elastic rocker	6552,57	918,82	±194,10

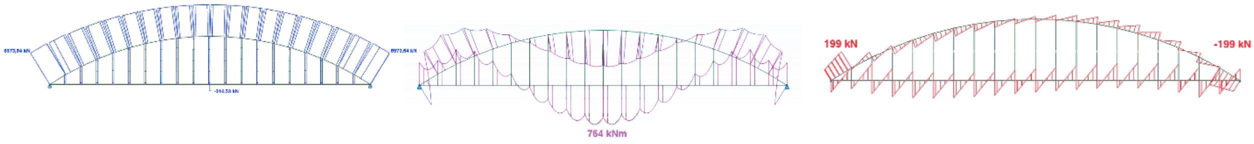


Fig. 6. Diagrams refer to Hinge-Hinge: (a) Normal stress – N_x (max); (b) Bending moment - M_y (max); (c) Shear - T_z(max).

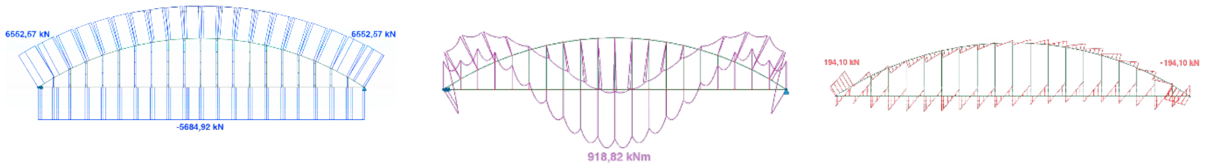


Fig. 7. Diagrams refer to Hinge-Elastic Rocket: (a) Normal stress – N_x (max); (b) Bending moment - M_y (max); (c) Shear - T_z(max)

Table 2. Verifications hinge - hinge / hinge – elastic rocker combinations

Combinations/Verifications	Normal Stress (kN)	Bending Moment (kN)	**Shear (kN)**
Hinge - Hinge	$N_{Ed} = 6573,64$ kN $N_{t,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} = 24041,952$ kN $N_{Ed} \leq N_{t,Rd}$√	$M_{Ed} = 764$ kNm $M_{t,Rd} = \frac{W_{ply} \cdot f_y}{\gamma_{M0}} = 18061$ kNm $M_{Ed} \leq M_{t,Rd}$√	$T_{Ed} = 199$ kN $T_{t,Rd} = \frac{A \cdot \frac{f_y}{\sqrt{3}}}{\gamma_{M0}} = 13880$ kN $T_{Ed} \leq T_{t,Rd}$√
Hinge – Elastic rocker	$N_{Ed} = 6552,57$ kN $Nt_{,Rd} = \frac{A \cdot f_y}{\gamma_{M0}} = 24041,952$ kN $N_{Ed} \leq N_{t,Rd}$√	$M_{Ed} = 918,82$ kNm $M_{t,Rd} = \frac{W_{ply} \cdot f_y}{\gamma_{M0}} = 18061$ kNm $M_{Ed} \leq M_{t,Rd}$√	$T_{Ed} = 194,10$ kN $T_{t,Rd} = \frac{A \cdot \frac{f_y}{\sqrt{3}}}{\gamma_{M0}} = 13880$ kN $T_{Ed} \leq T_{t,Rd}$√

5.2. Verification

Verification were carried out following the indications of the Euro Code in the section ENV 1993-1-1 Design of steel structure [10], and are related to the maximum values of the corrections and the breakdown of the beams with the following geometric characteristics:

- Area = 71100 mm^2
- Moment of Inertia J_y= 320,5332 · 10^8 mm^4
- Moment of Inertia J_z= 320,5332 · 10^8 mm^4
- Modulus of elasticity E = 20600 Mpa

- Yield strength f_y= 355 N/mm^2
- Resistance Module W_{ply}= 534,222 · 10^5 mm^3
- Resistance Module W_{plz}= 534,222 · 10^5 mm^3
- Partial Safety Coefficient γ_{M0} = 1,05

5.3. Constraining Reactions

Table 3. Table of constraining reactions on hinge - hinge / hinge – elastic rocker combinations

Combinations	R_A (kN)	R_B (kN)	H_A (kN)	H_B (kN)
Hinge - Hinge	3450,46	3450,46	-5669,64	5669,64
Hinge – Elastic rocker	3450,46	3450,46		

The results obtained for the restraining reactions of the foundation structures highlight how the lateral thrust of the arch, due to the geometry chosen in this particular case, is even more intense than that which we are entitled to derive from vertical loads, and therefore highlights how foundation structures must be designed to withstand this pressure [11]. As we wanted to demonstrate, the "bow string arch" model exempts the foundation structures from the solicitation produced by the lateral thrust of the arch which is absorbed by the deck which is stretched due to the aforementioned thrust. The foundations, for this case, will be slenderer and will weigh less on the ground than other models.

6. Verification of limit deformations

The N.T.C. 2018 in Chapter 5, concerning civil and industrial structures [9], and in particular in the sub-chapter concerning steel structures, suggests a limit to the size of the rise of the deformed configuration of the structure. The rise is calculated in correspondence of the maximum inflection. The standards impose that maximum deformations cannot overcome the range (1/300-1/500 L), with L = Length of the suspended deck (100 m), depending on the type of loads (permanent loads, or the latter added to accidental loads) (Fig.9(a), (b)).

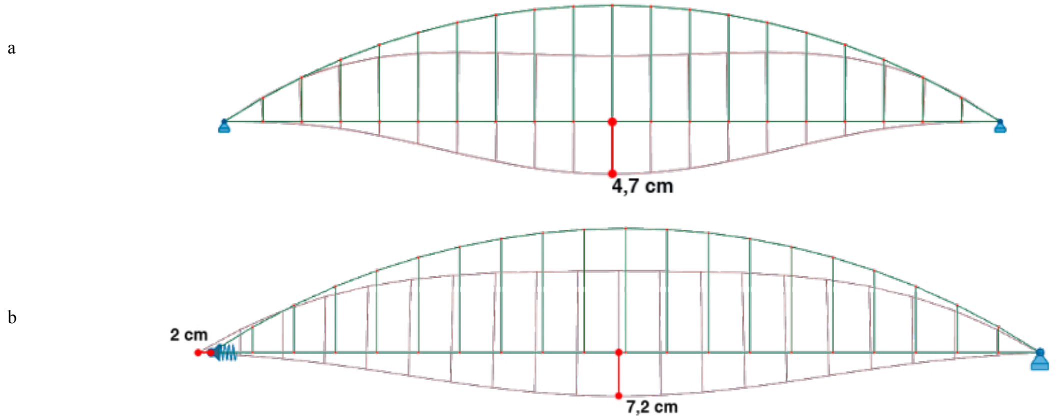


Fig. 8. (a) Limit hinge combination "hinge – hinge"; (b) "Hinge – elastic rocker" limit combination deformation.

$$\textit{Hinge - Hinge}\text{: } f \leq \frac{L}{500} \rightarrow 4{,}7\text{ cm} \leq \frac{10000\text{ cm}}{500} \rightarrow 4{,}7\text{ cm} \leq 20\text{ cm}\surd$$

$$\textit{Hinge – Elastic rocker}\text{ : Vertical: } f' \leq \frac{L}{500} \rightarrow 7{,}2\ cm \leq \frac{10000\ cm}{500} \rightarrow 7{,}2\ cm \leq 20\ cm\surd$$

$$\text{Horizontal: } f'' \leq \frac{H}{500} \rightarrow 2\ cm \leq \frac{1500\ cm}{500} \rightarrow 2cm \leq 3\ cm\surd$$

For horizontal displacements, it is advisable to consider the ratio with respect to the maximum height H = 15m.

7. Discussion and Concluding Remarks

From the study carried out on the two schemes adopted for the pedestrian bridge, some important information about the choice of the most suitable construction type can be extrapolated; in its physical constitution and in the parts inherent to the bridge itself, both alternatives leave the internal construction system unchanged, which enjoys a stability that is ensured by the "bowstring arch" model; with regard to the constitution of the external constraints or of the sites on which the bridge will rest once realized, the obtained constraining reactions necessary to balance the two systems result very different.

In particular, the first case analyzed ("hinge-hinge") is subjected to relatively lower internal stresses, above all with regard to normal stress and bending moment in the deck beam, and moreover, it has a lower maximum inflection (4.7cm) with respect to the "elastic hinge - roller". The advantages of this latter scheme, on the other hand, are given by the reactions at supports arising from this system. In the event that one of the two constraints is a resilient carriage, the support reactions to which the foundation structures must face are only and exclusively vertical. A further advantage is given by the possibility to move under the effect of thermal loads which, especially in structures made entirely of steel, heavily affect the internal stresses. This advantage has not to be underestimated, especially in cases of less rigid soils, that require larger foundation structures; the creation of a "string bow" system could in fact guarantee a greater slenderness of the foundations and therefore greater safety in the case of fragile and poorly resistant soils. On the other hand, obviously, greater attention should be paid to the secondary elements of the bridge, which, in this case, are also subject to the same inflection of the structure as a whole; this problem could be overcome by the realization of a counter-arrow deck, with an initial curvature opposite to the one of the deformed configuration, and which therefore could avoid the excessive embarkation of the structure.

Therefore, the choices made on both cases will concern the design of the structure foundations, while the geometric and physical characteristics of the bridge elements, and then the aesthetic appearance, remain unchanged.

Finally this contribution has highlighted how it is possible to design the entire structure through parametric design, from the design idea to the definition of the construction details.

Acknowledgements

This research has been supported by the OptArch project: “Optimization Driven Architectural Design of Structures” (No: 689983) belonging to the Marie Skłodowska-Curie Actions (MSCA) Research and Innovation Staff Exchange (RISE) H2020-MSCA-RISE-2015.

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