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ON THE OPTIMAL DESIGN OF CABLE-STAYED BRIDGES

G. Carpentieri[1], M. Modano[2], F. Fabbrocino[3], L. Feo[1], and F. Fraternali[1]

[1] Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano (SA), Italy, {gcarpentieri, l.feo}@unisa.it

[2] Department of Civil Engineering, "Federico II" University of Naples, Via Claudio 21, 80125 Naples, Italy, email: modano@unina.it

[3] Department of Engineering, Pegaso University, Piazza Trieste e Trento 48, 80132 Naples, Italy, email: francesco.fabbrocino@unipegaso.it

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Abstract. *This paper studies cable-stayed bridges (CBSs), with special focus on the initial force distributions in cables during construction phases. An algorithm for the optimal design of the pre-tensioning sequence of cables is presented. A procedure for the optimization of cable forces is developed, according to a given objective function. Particular attention is given to the choice of the parameters to be optimized, and numeric examples are provided. The proposed method is employed to study the At Tannumah bridge in Basrah, Iraq; and is suitable for the optimization of the pre-tensioning sequence of arbitrary cable-stayed bridges.*
We show in the rest of the paper that an initial design (named S_0 configuration) that does not include any pre-tensioning forces in cables can lead to a highly non uniform bending moment distribution over the deck; which is not ideal for an optimal structure. Fort that reason we develop an "optimal design" (named S_d configuration), that corresponds to pre-tensioning forces inducing an "optimal" bending moment distribution over the deck.

1 INTRODUCTION

The construction of cable-stayed bridges is characterized by a series of phases in which geometry, boundaries, and loads vary significantly, causing changes in the state of stress [1-9]. The optimization of the construction process via the regulation of the initial forces in cables is important for the optimal control of the whole structural behavior [10-16]. One of the most common problems dealing with cable-stayed bridges concerns the computing of the initial cable forces and the pre-tensioning sequence, needed to obtain the designed configuration [17-20]. An optimal pre-tensioning sequence is useful for the control of the state of stress and strain during and after the construction phases. This question is faced in literature with several approaches [8,9,14], and is nowadays an open issue. In fact, there aren’t closed form analytical solutions that allow the computing of the pre-tensioning sequence given a final design configuration. Only iterative algorithms are available [8,9,14], but such approaches require several cable tightening operations that cause technological, structural, and economic problems.

The absence of closed form solutions to this problem is due to the large number of parameters needed to characterize the cable stress distribution in CSBs. In fact, the structural behavior of CSBs depends on geometry, statics, material properties, construction process, and technology. The development of tools that allow the control of the behavior of these structures is therefore an open issue.

The present work deals with the formulation of procedure for the optimization of cable pre-tensioning forces that is suitable for any kind of CSBs. The proposed approach allows for the optimization of the bending moment distribution in the deck under suitable values of the pre-tensioning forces. We employ the “influence matrix method” [18] to compute the optimal pre-tensioning sequence that guarantee the achievement of the designed bending moment distribution (BMD) which is statically equivalent to another target distribution.

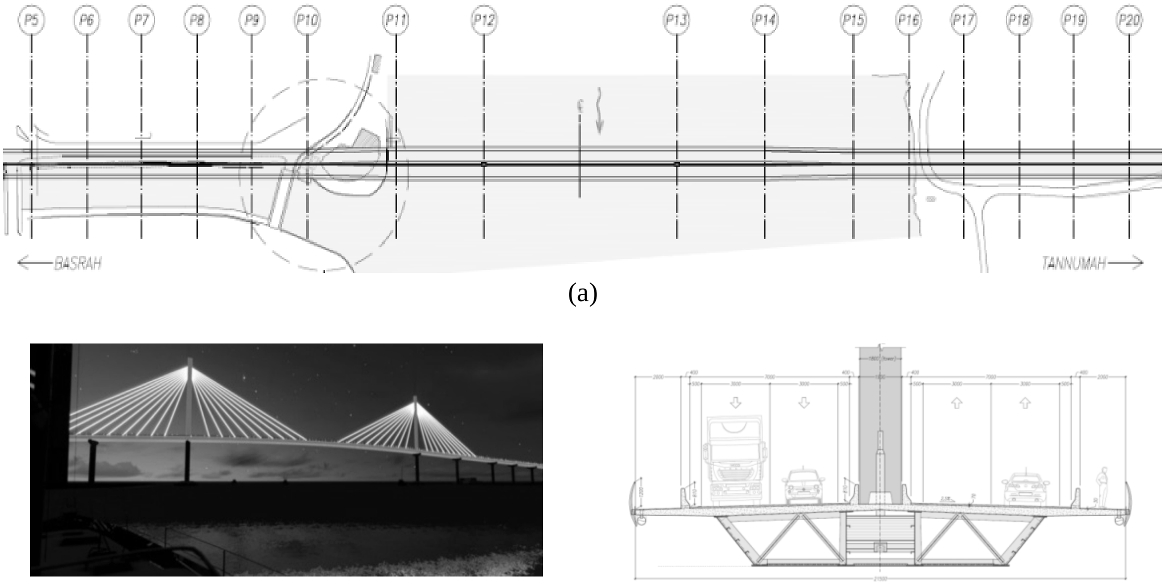
The procedure belongs to the “force equilibrium methods” [11], acting directly on the internal forces and indirectly on the elastic deformations. The proposed procedure is suitable for any construction sequence, and can be generalized to account for time-dependent phenomena [21].

2 DESCRIPTION OF THE CASE STUDY

The At Tannumah Bridge (ATB) has been designed by Studio “De Miranda Associati”, Milan, Italy and it is a part of a highway viaduct that connects the city center of Basra to the area of At Tannumah, Iraq, passing over the Shatt al Arab River.

The bridge concept include a semi-fan, central suspended span and self-supported cable-stayed system. In the longitudinal direction, the bridge is symmetric with respect to the mid-span, and it include two towers and two set of cables. The deck is made of three spans, the central one of 150 m and two lateral ones of 75 m each. The deck is obtained assembly semi-precast elements with length of 12.50 m each. The towers are made of pre-built sections of reinforced high-strength concrete (class C45/55 according to the Eurocode 2 [22]). The deck is made of steel welded beams (class S355 [22]) and reinforced concrete sections (a concrete slab of class C25/30 [22], 26 cm thick). The connection between the concrete slab and the steel beams is made through metallic bolts. The cables have a total diameter of 22 cm and are made of a set of 110 braided steel wires with diameter of 16 mm each.

Fig. 1 shows different views of the ATB, while Fig. 2 illustrates the layout of the structural model that we employed to describe such a bridge. The elastic problem of the CSB model in Fig. 2 has been solved on assuming linear elastic response of all the bridge elements, through the numerical algorithm that is detailed in [16]. We refer the reader to [16] for the mechanical and geometric properties of all the bridge elements.



(a)

(b)

(c)

Figure 1: The At Tannumah Bridge: (a) top view, (b) 3d view, (c) cross sectional [16] (courtesy of Studio “De Miranda Associati”, Milan, Italy).

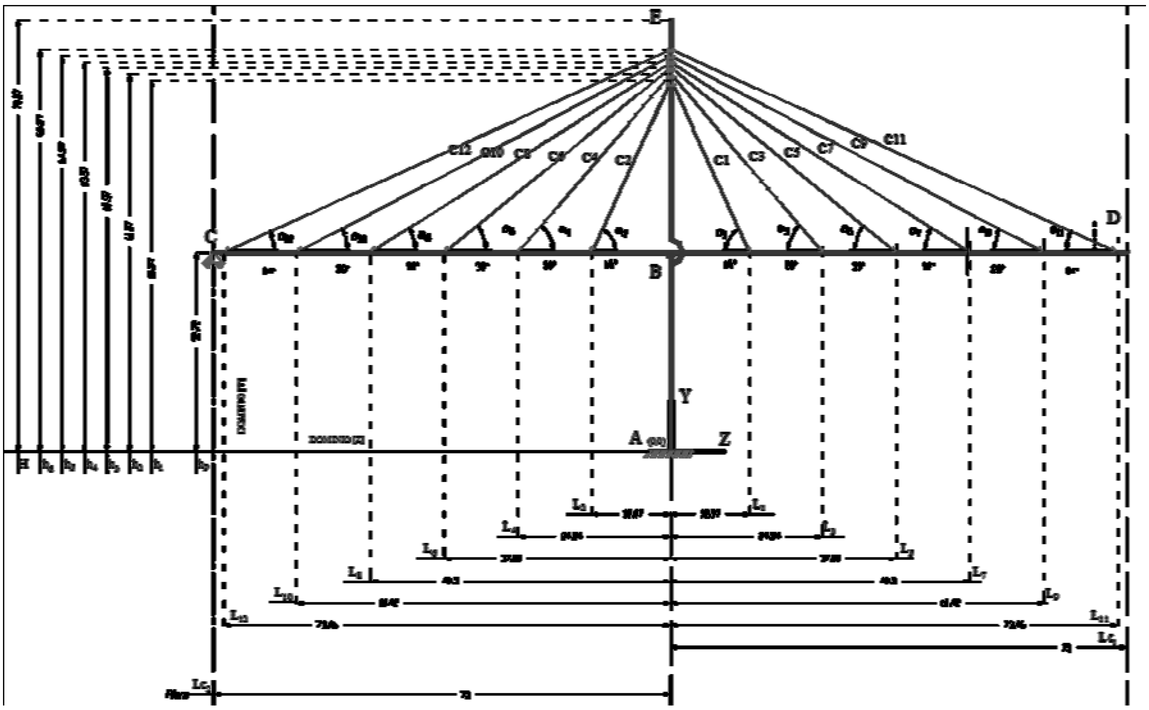


Figure 2: Bridge model.

Hereafter, we name “initial” (Fig. 3a) the bridge model S_0 that corresponds to assuming zero pre-tensioning forces in the cables (bridge unstressed under zero external loads). We shall see in the next section that such a model induces a highly non uniform moment distribution over the deck, which is not ideal for an optimal use of the material (assuming uniform cross section of the deck along the span).

We instead name "optimal design" (Fig. 3b) the realization S_d of the bridge model in Fig. 2 that corresponds to pre-tensioning forces inducing a bending moment distribution over the deck identical to that of a low-stiffness deck model under zero pre-tensioning ("optimal" bending moment distribution). It is shown in [16] that such a bending moment distribution is nearly uniform over the span, determining an optimized use of the material composing the deck, which is assumed to have uniform cross-section. It is worth noting that the bridge model S_0, accounts for self-weight, external loads and the major dynamic effects (such as, e.g., wind and fluttering). The proposed procedure allows to obtain a target bending moment distribution, through the application of a self-equilibrated state of stress induced by an optimal cable pre-tensioning. As a matter of fact, our final goal is to play with the pre-tensioning forces of the cables of the model in Fig. 2, in order to achieve such the above, optimal bending moment distribution on the ATB.

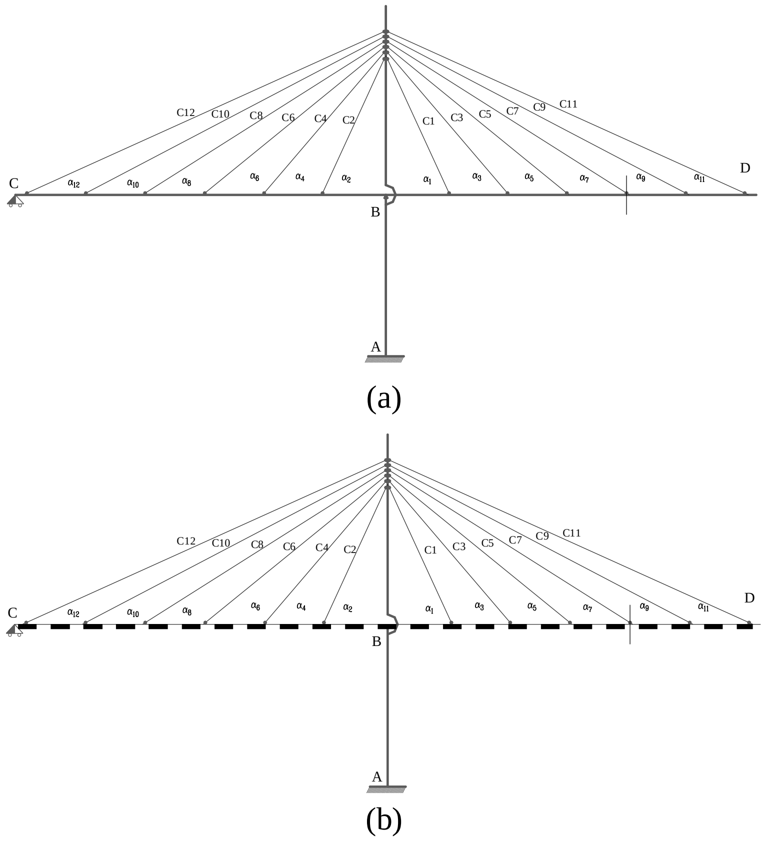


Figure 3: (a) initial bridge model S_0, (b) optimal bridge model S_d. The dashed thick line indicate a low stiffness deck.

3 NUMERICAL RESULTS FOR INITIAL AND OPTIMAL DESIGN MODELS

Figs. 4 and 5 show the bending moment and cable force distributions for the initial and optimal bridge models defined in the previous section. It is worth noting that the bending moment distribution of the initial model (M_0) is rather non uniform along the deck, featuring a pick value in correspondence of the deck-pier junction that is more than 5 times larger than the moment at the middle of the span (Fig. 4a). In the same model, the axial force carried by the most stressed cable (cable # 7) is 3.28 times larger than the axial force carried by cable # 1 (Fig. 4b).

The bending moment distribution (M_d) and the cable force distribution of the optimal design model are shown in Fig. 5a-b. We observe that M_d shows a much more uniform distribution over the span as compared to M_0 (Fig. 4a). The cable force distribution also shows a more uniform profile as compared to that of the initial model, featuring a maximum cable force (in cable # 9) that is 1.96 times larger than the force carried by cable # 1.

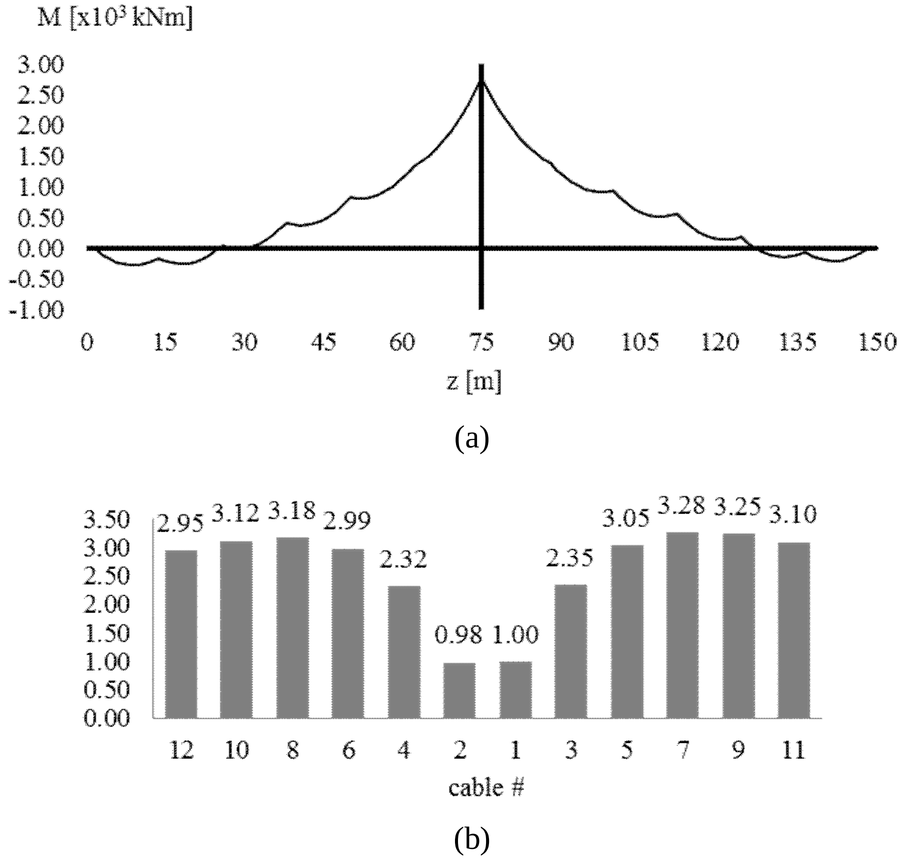
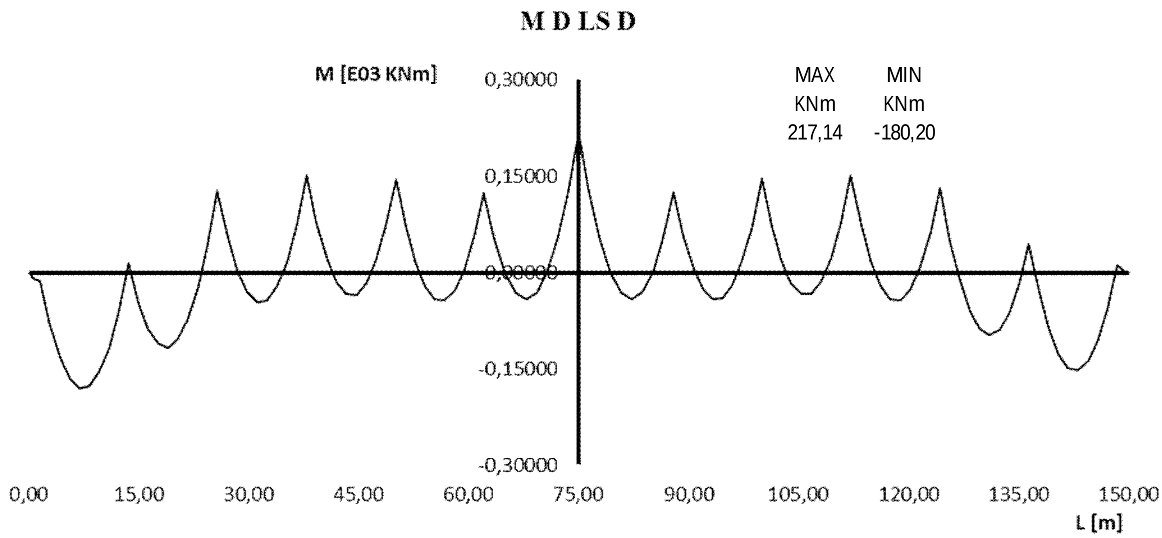
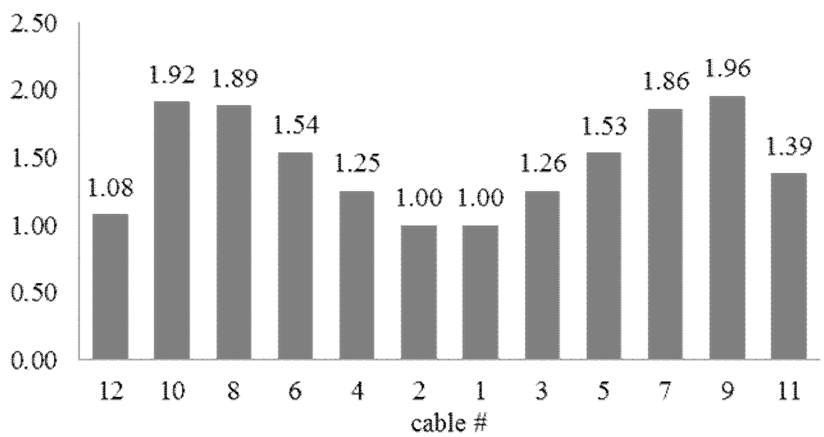


Figure 4: (a) bending moment and (b) normalized cable forces (divided by the axial force carried by cable # 1) for the initial model.

We recall that M_0 was computed on the real model of the ATB prescribing zero pretensioning forces in all cables. Such moment distribution resembles that of a cantilever beam under uniform transverse loading, on the initial portions of the two deck branches departing from the central pier (Fig. 4a). The M_d bending moment distribution was instead computed on a fictitious bridge model with a low stiffness deck [16]. Such moment distribution resembles that of a multi-support continuous beam under uniform transverse loading, always over the initial portions of the deck departing from the pier (Fig. 5a).



(a)



(b)

Figure 5: (a) bending moment and (b) normalized cable forces (divided by the axial force carried by cable # 1) for the optimal model.

4 OPTIMAL PRE-TENSIONING DESIGN

The present section is devoted to the formulation of a pre-tensioning design of the ATB model, which ensures that the bending moment distribution over the deck corresponds to M_d (Fig. 5a). Let $\boldsymbol{X} = \{x_1, \cdots x_n\}^T$ denote the vector collecting the pre-tensioning forces of all cables (n = 12). By repeatedly solving elastic problems of the bridge model in Fig. 2, we compute the axial force carried by the j-th cable when the i-th cable is subject to a unit axial force (S_i system). Let d_{ij} denote such a force coefficient and let **D** denote the n by n influence matrix collecting all such entries [16]. We are interested in solving the following linear problem [23]:

$$\mathbf{D}^T\,\mathbf{X} = \Delta\mathbf{T} \tag{1}$$

where $\boldsymbol{\Delta T} = \{\Delta t_1, \cdots \Delta t_n\}^T$ is the vector with current entry $\Delta t_i = t_{di} - t_{0i}$, t_{di} and t_{0i} respectively denoting the forces in the i-th cable in correspondence of the optimal design and in the initial models. The algebraic system of equations (1) is obtained by solving the n+2 elastic systems S_0, S_d, S_1, …, S_n. Its solution allows us to determine the pre-tensioning forces to be applied to the different cables in order to achieve the target bending moment distribution M_d (Fig. 5a).

5 CONCLUSIONS

We have presented an approach to the optimal pre-tensioning design of cable-stayed bridges that is aimed at achieving a target bending moment distribution over the deck. Such a design approach allows the designers to recover from construction errors that could compromise the structural safety of the bridge.

The proposed methodology is based on the matrix of influence method, and relies on the determination of the cable forces on n+2 elastic models, n denoting the total number of cables. It can be applied in correspondence with any construction phase and can be easily generalized to account time dependent phenomena due, e.g., to material viscosity [21], and/or fracture damage [24]. Such a bridge design technique can also be applied to prestressed concrete structures, arch bridges with suspended decks, and all prestressable structures [25]-[31]. Another field of application of the influence matrix approach proposed in the present work regards the study of the optimal state of prestress of tensile reinforcements of existing masonry structures[32]-[35].

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