Staging and Pretensioning of Cable-Stayed Bridges

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Abstract. This paper describes a study of cable-stayed bridges (CSBs), with a focus on the computation of the optimal pre-tensioning cable forces to be applied in the construction phase and the service behavior. We distinguish the case of a structure built using temporary supports from that of a structure built through the so-called cantilever method. We formulate an optimization procedure aimed at determining the cable pre-tensioning forces that ensure a target stress distribution along the longitudinal axis of the structure. The goal of this procedure is to make the bending diagram distribution as much uniform as possible over the bridge length, in order to avoid undesired stress localization effects. The proposed procedure is based on an influence matrix approach, and makes use of a single pre-tensioning cycle. It can be applied to optimize the mechanical response of the structure in any phase of its life cycle.

1. Introduction
One of the most common problem related to the design of cable-stayed structures is concerned with the determination of the initial cable forces, and the pre-tensioning sequences to be applied to such elements. An optimal pre-tensioning sequence is useful to control the stress and strain states exhibited by the structure, in correspondence with the construction phase, and also in the long-term behavior. The procedure presented in this work aims at directly solving the problem of cable pretension in cable-stayed structures, through a sensitivity analysis approach that can be applied to different construction techniques. Alternative approaches to the analyzed problem are available in the literature [1, 2], but there is a lack of analytical and explicit solutions. Available methods are typically based on iterative algorithms [3], which call for a progressive adjustments for the cable’s forces during the construction phase. Such approaches require recursive cable tightening operations, and may be affected by a number of technological, structural, and economical issues. The present procedure instead makes use of an influence matrix method [1-6], and uses a single pre-tensioning sequence, in order to achieve a given bending moment distribution along the longitudinal axis of the structure.
As compared to previous available works on the same topic [3-5], this paper presents new results on the application of the proposed optimization procedure to cable-stayed bridges realized through two different assembly procedures, namely: bridges whose construction phase employs temporary supports, and bridges built through the so-called cantilever method.

2. Construction phases and basic principles
The structure’s operational behavior is variously influenced by geometric, static and mechanical characteristics, constructive modalities, construction phases and techniques. The tools and procedures used to monitor and control the behaviour of these structures are then an important factor for the overall construction. The procedure can be applied to any type of cable-stayed bridge (CSB) once the design, mechanical system characteristics, and construction sequences and techniques are known. The method proposed in this paper is applied to a basic structure built with two different construction
procedures. In both cases, the method solves the optimisation problem and can then be considered a valid aid for the construction of CSBs.

2.1. Theoretical model and main hypothesis
The bridge idealised diagram includes a semi-fan, a central suspended span and a self-supported cable-stayed system. Towards the longitudinal direction, the bridge is symmetric with respect to the mid-span and it includes two towers and two sets of cables. The deck comprises three spans (i.e. the central span is 150m long, the two approaching spans are both 75m long) and assembled through semi-precast elements which are 12.50m long. The towers are made of pre-cast sections of reinforced high-strength concrete (C45/55). The deck is made of steel-welded beams (S355) and reinforced concrete sections (concrete slab (C25/30), 26cm thick). The concrete slab and the steel beams are connected using metallic bolts. The cables have a total diameter of 22 cm. The mono-dimensional model of the structure was developed to solve the elastic problem. The two-dimensional orthonormal system (OYZ), at this stage considered a mechanical model, represents the longitudinal profile of a continuous decked, semi-fanned, cable-stayed bridge with symmetrical spans and a cable inclination which varies between 65° and 25°. The geometric characteristics of the model described above are represented in the single-lined model shown below.

In addition to FEM modelling, the Principle of Virtual Works (PVW) was applied to develop the single-line models to assess the behavioral significance of the structure’s main mechanical parameters. The main hypothesis are:
- the pile is completely fixed to the base (point A);
- the internal span has a roller-type support at the final point C;
- the deck and tower are connected via an internal hinge;
- the cables have a symmetrical configuration in respect to the tower. They follow an odd ascending numeration on the central span (points B to D) and an even descending numeration on the internal span (points B to C);
- each normal plane section has a rigid range of motion, excluding warping deformation. The tower and the deck are considered mono-dimensional elements, in accordance with Euler-Bernoulli’s beam theory.

2.2. Sensitivity analysis
In order to apply the optimization procedure, different models of the structure were analyzed and a sensitivity analysis was carried out. This analysis aimed to define a domain in which the behaviour of the structure is placed. Many virtual models of the structure were created by varying the stiffness of the main elements (deck, pile, cables, antenna).
- High-stiffness deck (HSD) - Low-stiffness cables, pile, and antenna
- Low-stiffness deck (LSD) - High-stiffness cables, pile and antenna
- High-stiffness tower [pyle and antenna together] (HST) - Low-stiffness deck and cables
- Low-stiffness antenna (LSA) - High-stiffness cables, deck, and pile
- High-stiffness cables (HSC) - Low-stiffness deck, pile, and antenna
- Low-stiffness cables (LSC) - High-stiffness deck, pile, and antenna
2.3. Case studies
Two models were analyzed to identify the behavior of the real structure. The first model was calculated for the construction phase related to the temporary supports method. The second model relates to the cantilever method. In both cases, comparative analyses were carried out together with the results obtained from the sensitivity analysis. It is useful to remember that the sensitivity analysis was developed to identify the best possible configuration of the stresses induced on the structure.

![Temporary supports method](image1.png)

Figure 3. Construction stage: Temporary supports method.

![Cantilever method](image2.png)

Figure 4. Construction stage: Cantilever method.

3. Proposed optimization procedure
The optimization of the initial cable forces was carried out by elaborating an analytical method based on the structure’s global equilibrium conditions. Taking an adequate parameter as a reference, the optimal entity of the initial cable stresses was determined to obtain a specific distribution of the stress state in the final assembly configuration. The proposed method leads to a linear elastic analysis under the hypotheses of small displacements, with a consequent linear sum of effects, with the aim of reaching a predetermined distribution of bending moments on the deck. This method acts directly on the static entities and indirectly on the elastic deformations, nullifying the vertical displacement in the cable-to-deck connection. The problem has been formulated in terms of structural optimization. After a restrained structural system has been assigned and the precise load conditions defined, an optimal entity of the cable stressing sequences is sought to obtain a predetermined distribution of bending moments on the deck. The problem is reconstituted through the resolution of a linear algebraic system whose unknowns \( X = \{x_1, x_2, \ldots, x_n\} \) are the optimal pretension stresses to be applied to each cable in the \( C_0 \) configuration until the optimal stress configuration \( C_d \) is obtained under the same control load.

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By inverting the \( D \) matrix, it is possible to identify the group of pretension stresses to be applied to the cables in order to guarantee the desired conformation.

4. Numerical results
The results of the two case studies - CSB built with temporary supports and CSB built using cantilever method - are perfectly contained in the domain defined by the sensitivity analysis. Notably, the cantilever construction determines a more severe stress and strain state. In both cases, the method allows us to obtain a better configuration of the bending moment on the deck and a more uniform distribution of axial forces in the cables.
The optimal distribution was chosen from the multiple stress configurations and identified as an objective function. The solutions with compressive stresses in the cables were discarded. In the following figures are shown the diagrams of the moments obtained on the structures built with the two different construction methods. Figure 5 shows the bending moments on the deck in significant (virtual) configurations used in Sensivity Analysis: HSD – orange; LSD – light blue; Real config. of struct. – blue; HSC – green; LSC – red. Figures 6, 7 show cables axial forces in most significant (virtual) configurations used in Sensivity Analysis and in the real configuration of structure. The most important are: HSD – light blue; LSD – orange; Real config. of struct. – grey. The diagram of the bending moment on the deck obtained after applying the optimization procedure is shown in figure 9, that is bending moment diagram after applying the pretension stresses in the cables. Figures 10 and 11 show the improved distribution of axial force in the cables following the optimisation procedure. After pre-tensioning, the axial stresses in the cables become more uniform, improving the functioning of the structure.

The optimal configuration can be achieved for any given initial configuration: “temporary support” as well as “cantilever methods”. In both cases (T.S. and C.M.), the axial forces in the cables tend to be uniform, limiting the stress variations - compared to the 1st cable in span - from 3,8 to 1,8. In both cases there is also a drastic reduction of the bending moment on the deck. Bending moments are driven to the values of continuous beam on simple supports. In fact, the pretension in the cables generates positive bending moments that reduce negative moments on the deck.
5. Concluding remarks
We have presented an approach to the optimal pre-tensioning design of cable-stayed bridges which aims at achieving a target bending moment distribution over the deck. The proposed methodology is based on the matrix of influence method, and determines the cable forces that permit to avoid bending moment concentrations. It can be applied to any construction phase of the structure, and can be easily generalized to account time dependent phenomena due, e.g., to viscosity effects [7, 8]. The given results highlight that the optimization procedure illustrated in Ref. [3] can be suitably generalized to cover different construction techniques of cable stayed bridges. Such a generalization allows us to strengthen the applicative potential of this procedure in real-life examples. It is worth observing that the design technique proposed in the present work can also be applied to masonry structures [5], arch bridges with suspended decks, and all the prestressable structures [3, 7-14]. We address an experimental validation of this technique to future work, through the fabrication and testing of reduced-scale models [15-34], making use of innovative materials [15-34] and sustainable additive manufacturing techniques [15-34].

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