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Construction sequence analysis of long-span cable-stayed bridges

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ABSTRACT

In cantilever construction of long-span cable-stayed bridges the stressing sequence of stays is fundamental for establishing the final configuration of the bridge. The structural behaviour of these bridges is usually evaluated through a forward staged construction analysis, in which the values of the prestressing forces to be applied to stays are the main unknowns. A unified procedure for determining the initial cable forces and for analyzing the entire sequence is presented here, considering the geometric nonlinearity of stays through the Dischinger equivalent elastic modulus. The target is the simultaneous determination of the initial cable forces with the simulation of the construction stages in the forward analysis, taking into account the cable-sag effect, in order to achieve the required geometric configuration at the end of the sequence together with an advantageous state of stress for deck and pylon. Furthermore, a probabilistic approach is proposed for the evaluation of the effects that uncertainties of stay forces, occurring in the actual stressing sequences on site, have on the bridge behaviour. With this purpose probable errors during the real work operations on site are considered here in addition to the theoretical analysis of construction stages. Finally, the evaluation of the reliability of the proposed procedure is tested on a case-study of a long-span cable-stayed bridge, considering the influence of the deck typology on the stressing sequence.

1. Introduction

The cantilever construction of cable-stayed bridges is characterized by a sequence of construction stages in which geometry, restraints and loads vary many times and significantly, influencing the overall behaviour of the bridge. It follows that stress and deformation patterns vary several times until reaching the final configuration. Hence the evaluation of the structural behaviour of cable-stayed bridges during construction is usually carried out by means of an analysis in progress called “forward analysis.” In cable-stayed bridges, however, a forward structural analysis is possible only if the initial cable forces are known, a priori, i.e. the prestressing forces to be assigned to each stay are established through an independent procedure carried out before the forward analysis of the sequence. In this way the two phases of design (analysis of the structural behaviour and evaluation of initial cable forces) are carried out separately, although they are closely interdependent. If the prestressing forces are not assessed by a good criterion, the evolution of stress and strain in the bridge elements, during and after construction, may differ significantly from the expected one, with the final result of unacceptable states of stress or deformation, especially in view of serviceability. Several adjustments of stay stressing are necessary, compromising and limiting the functionality and usability, with obvious consequences from the technological and economic points of view.

In the new generation of cable-stayed bridges, the reduction of the spacing between stays as well as the increasing lightness and strength of new materials has led to the introduction of decks with greater deformability, thereby increasing the influence that prestressing forces allocated to stays have on the overall structural behaviour of the bridge.

It follows that the design and analysis of the construction sequence of long-span cable-stayed bridges can be traced back to the assessment of the stressing sequence, i.e. to the evaluation of the initial cable forces to be assigned to the stays during construction and to the evaluation of the allocation sequence of such forces.

The state of the art of the prestressing force evaluation methods is complex and ramified.

The methods that allow designers to assess the initial cable forces, whether they operate with backward or forward analyses, are substantially distinguishable into three categories: Displacement method [1], Force equilibrium method [2] or Unit load method [3], Optimization method [4]. In Chen & Duan [5] the optimization of cable forces is done by minimizing the potential energy under the condition of established range of stay stresses and pylon displacements. Martins et al. [6] optimize cable forces in concrete cable-stayed bridges, considering

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nonlinearity and taking the deck stresses as objective functions. Simões & Negrão [7] presented a geometric optimization of cable-stayed bridges through a multi-objective mathematical function which takes into account the minimum cost and stresses. Cid et al. [8] and Sung et al. [9] presented optimization methods in which the optimization target function is established in order to modify the results obtained by the construction sequence, changing one or more parameters in the construction stages. The optimization is usually applied to the final scheme, i.e. to the completed bridge, considered as the result of the construction sequence and the optimization of the bridge components (deck, stays, pylon) becomes a separate procedure from that of the initial cable force determination. In this connection "cable-stayed bridge optimization" is conceptually different from the problem of cable force determination because the optimization method supplies the optimal behaviour of the bridge components, which is a problem of conceptual design; hence the bridge elements can be varied and optimized together with the set of stay forces. In the problem of initial cable force determination instead, the bridge components and their properties are already established and the values of stay prestressing are evaluated in direct correlation to the actual sequence of construction.

In literature many methods solve the problem of assessing initial cable forces directly on the final scheme ignoring the evolution of the state of stress and strain due to the construction of segments as well as the effects of geometric nonlinearity of the stays and creep-shrinkage phenomena of concrete in composite decks. From the first studies the same methodologies were extended to take into account the cantilever construction effects and the geometric nonlinearity of the stays [10]. Other authors considered these effects from the beginning [11,12]. In fact, an important aspect to be considered in the stressing sequence is the influence of the cable-sag effect, especially for medium and long spans. The bridge span and the length of stays emphasize this phenomenon, which cannot be overlooked, leading otherwise to results affected by sensitive and obvious errors. Long span steel bridges, as a result of their dimensions, emphasize the effects of the geometric nonlinearity of stays [13].

A further important aspect that influences evaluation of the stressing sequence of the stays is the deck typology. The decks of cable-stayed bridges can be of three different typologies: prestressed concrete girders or boxes, steel-concrete composite cross sections and full steel sections. This variability is mainly due to the wide range of span lengths covered by these bridges, from 100 m to 1000 m, as well as to the costs of the different solutions adopted among these typologies [14,15]. When the bridge is built by the cantilever method, the deck typology can have different consequences in term of stress and strain patterns, especially in the determination of initial cable forces and stay stressing sequence. The steel-concrete composite deck is built in two steps: first the steel elements are assembled by cantilevering to the previous segment already built and then the concrete slab is cast over them and the stay attached and tensioned [16]. This operation leads to a fundamental difference between concrete and composite decks. In concrete decks the dead load is applied at once and the stay is stressed by referring directly to the entire value of the self-weight, both for the cast in situ technique and for the prefabricated segments. By contrast, in composite structures the dead load is applied at two subsequent times at each phase of construction. Hence the cross-section, related to the new segment built, changes; in fact it is only made of steel at first and becomes composite afterwards. As a consequence the evaluation of the initial cable forces and the following stressing sequence of stays are different for concrete and composite decks. In bridges with decks made entirely of steel, after the cantilever segment is assembled and the stay is attached, the latter is immediately stressed with its prestressing force.

For short-span bridges with linear behaviour of stays, the authors developed the Partial Elastic Scheme Method (PES Method). It is a simple procedure for evaluation of initial cable forces for concrete and composite cable-stayed bridges built by cantilevering [17,18] and for arch bridges [19]. Initial cable force determination is performed through partial elastic schemes of the structure (Fig. 1a), one for each construction phase, i.e. for each segment assembled by cantilevering and for each stay attached and tensioned. Hence, each partial elastic scheme is an independent structural scheme with its geometry and its loads applied, useful for determining initial cable forces and solved by a static elastic scheme independent of the staged construction analysis.

The determination of initial cable forces can be done by applying the displacement or the force method. In the displacement method, the design constraints are expressed in terms of displacement requirements while in the force method they are set in terms of static requirements. The first case occurs when the geometric configuration has to be reached during and/or after the construction sequence while the second case occurs when the target is to define an advantageous bending moment diagram or an advantageous distribution of stay forces during and at the end of construction. In both cases, it is important to choose the smallest number of constraints for good mathematical conditioning

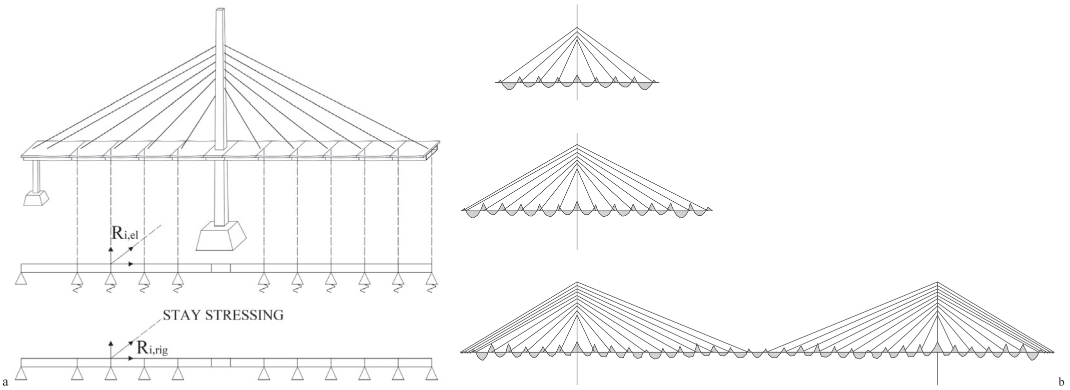

Fig. 1. (a) The PES concept at the generic construction stage with application of the zero-displacement method. (b) Achievement of continuous beam behaviour in different partial schemes of the construction sequence.