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An algorithm for simulation of concrete cable-stayed bridges built on temporary supports and considering time dependent effects

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ABSTRACT

The time-dependent phenomena effects might play an important role in the structural behavior of a cable-stayed bridge during construction and in service. In fact, because of these effects the target state of stresses (Objective Service Stage, *OSS*) can only be achieved at a certain target time. In the literature, a number of software have been presented to study creep and shrinkage effects during cantilever erection of cable-stayed bridges. Nevertheless, the effects of these phenomena in the alternative erection technique, the temporary support erection method, have received little attention. Furthermore, none of the presented software are able to: (1) Define a determined OSS for a given time including the time-dependent phenomena effects and the evolutionary erection of the superstructure. (2) Simulate the construction process assuring the achievement of a given OSS without the need of an overall iterative process taking into account time-dependent phenomena. (3) Provide the prestressing sequence in such a way that no additional tensioning operations are required to correct creep and shrinkage effects in service. To fill all these gaps, a new algorithm, the Forward-Direct Algorithm (FDA), is formally presented in this paper to simulate the construction process of cable-stayed bridges built on temporary supports. The main innovation of this algorithm consists of introducing the time-dependent phenomena effects into the unstressed length of the stays concept to calculate the prestressing strains to be introduced during the last re-tensioning operation. The application of the unstressed length concept has major advantages both in the simulation (as the OSS can be achieved without any overall iterative process) and in service (as re-tensioning operations to correct time-dependent phenomena effects can be avoided). To illustrate the creep and shrinkage effects during the construction and in service the FDA is applied to a real cable-stayed bridge. Furthermore, an analysis to define the optimum time to achieve the OSS is presented.

1. Introduction

Mid- and long-span cable-stayed bridge superstructures are rarely built in a single operation. In these structures, staggered erection is traditionally used to accelerate construction and to minimize erection costs. There are mainly four constructions methods for this kind of bridges: the cantilever erection method, traditionally used in environmentally sensitive and difficult to access locations (see [1]), incremental launching, where usually the deck is built in one abutment and it is launched to its final position being supported on temporary supports (even though there are some variations, see [2]), the temporary supports erection method, where the deck is cast on scaffolding [2], or the rotation method, where the deck is built on temporary supports and afterwards lifted due to the prestressing of the cables and rotated into its final position [3]. The last three construction methods require temporary bearing of the deck during the construction of the superstructure. The choice of the construction technique takes into account schedule, economy and available technology.

The erection process of the cable-stayed bridges plays also an important role in the geometry and stress state of the structure both during construction and in service. Among the different effects to take into account in the calculations, it is to highlight that time-dependent phenomena might be neglected in moderate size cable-stayed bridges made out of steel [4] or precast concrete segments [5], but their effect should not be neglected for long span bridges, mainly if they are made out of in situ concrete. In order to complete the design of a cable-stayed bridge, an adequate simulation of its erection sequence is required to guarantee that allowable stresses and deflections are not exceeded during construction.

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This simulation is associated with a number of computational difficulties (for example, due to the statically redundancy of the structure each time a stay is prestressed the forces of the rest of the stays are changed). To overcome these difficulties, several researchers have recommended methods based on the backward approach in the cantilever (see [6]) and in the temporary support erection method (see [7]). In this approach, the configuration of any partial structure is determined by disassembling the bridge according to the opposite erection sequence followed on site. The main inconvenient of this approach is the difficulty of modeling time-dependent phenomena, such as creep or shrinkage. To avoid these problems, a forward modeling has been proposed for the cantilever (see [8]) and the temporary supports erection method (see [9]). The main trade off of a forward simulation is that overall iterative processes are usually required making the computation more time consuming and complex. To avoid the need of the overall iterative process, an alternative process based on a direct simulation (the Direct Algorithm, *DA*) that does not require the application of the superposition of stages principle is presented in [4]. Although much work has been done on the simulation of concrete cantilevered structures, the effects of concrete time-dependent phenomena in the temporary support erection method have received relatively little attention as most of the methods in the literature are proposed for steel structures.

One of the first stages in the design of the construction process of a cable-stayed bridge is the definition of a target geometry and/or stress state, known as the Objective Service Stage (*OSS*), to be achieved at a certain time. This *OSS* might be defined by a number of criteria. Examples of these criteria are as follows: minimize the bending energy of the structure [10,11], assure that the axial forces of the stay cables produce the same bending moments as an equivalent fictitious continuous beam (Rigidly Continuous Beam Criterion [12]) or assure that the deflections at some target points are zero (Zero Deflection Criterion [13]). In this paper, the *OSS* is defined in terms of axial forces in the stay cables.

In concrete structures, the *OSS* depends, to a great extent, on the time-dependent phenomena effects. In fact, the stress state in service varies with time, and the *OSS* can only be obtained at a given target time, t_T. Some works (see [14–20]) have studied the time-dependent phenomena effects in cable-stayed bridges. Nevertheless, literature review (see [21–25]) shows that time-dependent phenomena effects are rarely included into the definition of the stay cable forces in the *OSS*. As the *OSS* depends on the t_T, additional questions, such as if it is better to define t_T at short-term or long-term, appear. Furthermore, in evolutionary erected structures (such as cable-stayed bridges on temporary supports), the structural system in which each load is applied (e.g. stay prestressing) is of primary importance when determining the time-dependent phenomena effects. In service, stays will indeed lose force due to these phenomena. Therefore, one or two re-stressing operation might be planned during the life time of concrete cable-stayed bridges to compensate time dependent effects. However, re-tensioning of these bridges, may lead to some uncertainties, especially if their stays are not long enough to use the strand by strand re-stressing technique. This is due to the fact that the wedges cannot grip twice in the same area of the strand. This implies that the whole stay should re-tensioned at the same time causing the following problems: (1) Some strands might be overtensioned. (2) For short stays the anchorage setting loss can affect very much the final force in the stay. (3) There are uncertainties also in the bridge response, not being sure of what is the final stress in the other stays once the last cable is tensioned. Moreover, re-stressing operations imply cost.

To answer all these questions this paper studies the creep and shrinkage effects throughout the construction process of cable-stayed bridges built on temporary supports. To evaluate the role of these phenomena, a new algorithm, the Forward-Direct Algorithm (*FDA*), is presented. This algorithm takes advantage of the application of the unstressed length of the stays concept to avoid the requirement of overall iterative processes, reducing computation time and simplifying computation. With the proposed algorithm the engineer is provided with a tool that might be used to reduce the number of re-stressing operations. As time-dependent phenomena effects are always present in both concrete and composite bridges, the designer can choose what is more economical: using additional tensioning operations in service to correct these effects or avoiding these additional tensioning operations by taking into account these effects during the calculations done in the design process. If this last choice is done, stay forces can be incremented and deck and towers can be precambered to mitigate the effects of the time-dependent phenomena.

This paper is organized as follows: In Section 2, a procedure to include the time-dependent phenomena into the definition of the unstressed lengths of the stay cables is presented. In Section 3, the main hypotheses and flow charts of the *FDA* are presented. In Section 4, this algorithm is applied to a real cable-stayed bridge calculated by different tensioning processes. Finally, some conclusions are drawn in Section 5.

2. Simulation of the time-dependent phenomena effects

In this section the unstressed length of the stays concept and their applications are first reviewed. In order to extend the applicability of the unstressed length concept, a procedure to include the time-dependent phenomena effects in the definition of the *OSS* is presented in the second part of the section.

2.1. Unstressed length of the stays

The unstressed length of a given stay, L_{0n}, corresponds with the length of an equivalent prefabricated stay that has to be placed on site to achieve the target structural behavior defined by the Objective Service Stage (*OSS*). This length is an intrinsic parameter that is independent of the conditions to which the stay is subjected on site. L_{0n} is shorter than the length of the corresponding stay in the un-deformed geometry of the *FEM* of the bridge, L_n. In the construction process, it is necessary to deform and stress the stay on site from L_{0n} until its ends occupy the position of the anchorages in the deformed geometry. This stress changes the geometry of the bridge and the stay length is changed from L_{0n} to the stressed length L_{Sn}.

With N_n being the axial force of this stay, E_n being the Elastic modulus of the cable material and A_n its cross sectional area, L_{0n} can be determined from L_{Sn} as presented in Eq. (1). The unstressed length concept remains applicable when the catenary effect is taken into account. In this case L_{Sn} must be substituted by the length of the catenary, L_{Cn} as shown in Eq. (2).

$$L_{0n} \approx L_{\mathrm{S}n} - \frac{N_n}{E_n A_n} L_{\mathrm{S}n} \tag{1}$$

$$L_{0n} \approx L_{\mathrm{C}n} - \frac{N_n}{E_n A_n} L_{\mathrm{C}n} \tag{2}$$

The unstressed length concept might be introduced into the simulation of the construction process of cable-stayed bridges. To do so, it might be assumed that extending a L_{0n} length stay on site to get a given force N_n produces the same effect that shortening an L_n stay in the model to get such force. This shortening can be