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Direct simulation of the tensioning process of cable-stayed bridges

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ABSTRACT

This paper proposes a new and innovative algorithm, the Direct Algorithm (*DA*), which introduces, for the very first time, the unstressed length of the stays concept into the modeling of the construction process of cable-stayed bridges. This assumption enables a fast and direct simulation of construction stages by analyzing independent Finite Element Models when time-dependent phenomena are neglected. The computational speed and the limited computer storing requirements of the *DA* make it especially indicated for optimization problems. Furthermore, it can be implemented in any structural analysis software.

1. Introduction

One of the first stages in the design of a cable-stayed bridge is the definition of a target stress state or geometry to be achieved in service in a stage known as the Objective Service Stage (*OSS*) [1]. This in practice leads to define an appropriate set of stay forces [2,3]. The definition of an adequate construction process that enables the achievement of the *OSS* on site is a complex nonlinear problem as during construction the structural system does not remain constant and partial structures arise. These partial structures are more flexible than the completed bridge and are subjected to construction loads. Thus, the effects of dynamic loads, such as wind [4,5] or earthquake [6], during construction can be even more significant than in the completed bridge. Furthermore, as cable-stayed bridges are highly statically redundant structures, tensioning one single cable or removing a temporary support affect the stresses in cables, supports, pylon and deck. For these reasons, many researchers have recommended the complete simulation of the construction process of cable stayed-bridges (see [7–9]). The objective of this simulation is double. On the one hand, guaranteeing that the limit states are not exceeded during erection and, on the other hand, defining a tensioning process that guarantees the achievement of the *OSS* at the end of the construction process. In the last decades, the development the Health Monitoring field [10] enables the structural control [6] and damage detection [11,12] of complex structures. Cable-stayed bridges used to be monitored both during construction and in service. The information obtained by monitoring systems can be used to calibrate simulation models that must be linked with maintenance and structural management to assure structural safety and functionally of structures [13]. This can also be used to monitor the construction process, ensuring that the tensioning process is followed according to the designer specifications.

The traditional method to simulate the construction process of cable-stayed bridges is to start at the *OSS* and gradually reduce the structure (backward simulation) stage by stage until the first construction stage is reached. Several authors have proposed methods based on the backward approach for the cantilever (see [14–16]) and the temporary support erection method (see [1]) The methods based on the backward approach are the most likely to achieve the fastest result as they start from a structurally correct solution (the final stage). Nevertheless, these methods are not adequate when deviations during the tensioning process of the structure appear. Furthermore, they can only approximate the effects of the time-dependent phenomena, (such as creep and shrinkage in concrete elements (see [17,18])) when a global iterative process or a backward-forward analysis is performed. To overcome all these problems, a forward simulation, which follows the erection sequence on site, has been proposed for the cantilever (see [14,15]) and the temporary supports erection method (see [19,20]). The main trade off of the forward simulation is that it is time consuming

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as an Overall Iterative Process is required to assure the achievement of the *OSS* at completion.

Most of the simulation methods presented in the literature assume that any construction stage can be obtained by deactivating or activating group of elements, loads or boundary conditions from the following or the preceding construction stages. This hypothesis assumes that the construction process can be simulated by linear superposition of stages (see [1,19]). The drawback of this simulation is that information from the following (backward approach) or the preceding (forward approach) construction stages is required. Therefore, geometry and stress state of intermediate construction stages cannot be directly analyzed (that is without simulating all the following or preceding construction stages) and the simulation is more time consuming. Furthermore, the whole geometry and stress state history of the preceding or following construction stages have to be stored. It is to highlight that both the computation time and the computer storing capacity are of critical importance when the construction process is introduced into any optimization process [21–24]. An alternative to the superposition principle, in which each construction stage is analyzed by an iterative process named "shape finding analysis", is proposed in [14]. The fact that an iterative process is required to define each construction stage is time consuming.

To overcome all these problems, a new and innovative algorithm, the Direct Algorithm (*DA*), is proposed in this paper for the direct simulation of the construction process of cable-stayed bridges. This algorithm is applied to the temporary support erection method. In this construction process, the bridge superstructure is first erected on a set of temporary and permanent supports and then, during the tensioning process, the load counterbalanced by the temporary supports is successively transmitted to the stay system (see [25]).

The *DA* introduces, for the very first time, the unstressed length of the stays concept into the simulation of the construction process of cable-stayed bridges. Using this concept enables a simulation of the geometry and stress state of intermediate construction stages without applying the superposition of stages principle. A simulation without the superposition principle has many advantages. For example any construction stage can be analyzed directly by an independent Finite Element Model (*FEM*) as no information from the following or the preceding construction stages is required. Furthermore, forward simulation without any overall iterative process can be carried out. The main trade off of not using the superposition principle is that time-dependent phenomena cannot be easily simulated. Hence, *DA* is proposed here for steel bridges. However, as in many bridges designers neglect the effects of these phenomena, the method still might be applied by many practitioners in the initial design and construction of concrete structures. The *DA* is characterized by its simplicity and it can be implemented in any structural analysis software that computes temperature increments or imposed strains. All these characteristics make the *DA* especially suited for optimization problems.

The paper is organized as follows: In Section 2, the main hypotheses of the *DA* are explained. In Section 3, the *DA* is compared with two alternative methods proposed in the literature (the Backward Algorithm, *BA*, and the Forward Algorithm, *FA*). In Section 4, the application of the *DA* to simulate the construction process of a cable-stayed bridge is presented. Furthermore, the results of the *DA* are compared with those obtained by the *FA*. Finally, in Section 5 some conclusions are drawn.

2. Direct algorithm

In this section, one of the main innovations of the Direct Algorithm (*DA*), the application of the unstressed length of the stays concept into the simulation of the construction process of cable-stayed bridges, is first described. Then, the simulation of the unstressed lengths by mean of imposed strains in the stays in the Objective Service Stage (*OSS*), ε^{OSS}, is presented. Next, the simulation of the tensioning process of the *DA* is described. Then, the Local Iterative Process (Local IP) required to simulate the raising of the temporary supports during the tensining process is presented. Next, the computation time of the *DA* is analyzed. Finally, the flowchart of the *DA* is presented, the algorithm is applied to a specific case study, and its results are compared to those given by other alternative methods proposed in the literature.

2.1. Unstressed length of the stays concept

A length-based adjustment is sometimes used to introduce the tensioning of the stays on site. This is the case of cable-stayed bridges with prefabricated cables. In this procedure, the stay n is made to accurately measure a so called unstressed or neutral length, L_{0n}. This is the length of a given cable (n) when it does not have any axial stress or strain. This length is measured when the cable rests horizontally on a support that counterbalances the effects of its own self weight (see Fig. 1(A)). The unstressed length is an intrinsic parameter that is independent of the conditions to which the stay is subjected on site. In Fig. 1(A) L_{0n} is compared with the length of the same stay in the un-deformed geometry on the *FEM* of the bridge, L_n, this is to say, the length given to the stay element in the stiffness matrix when neither loads nor imposed strains are applied in any element of the model. In the construction process, it is necessary to 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} as presented in Fig. 1(B). This elongation of the stay is equivalent of introducing an imposed strain ε_n. With ΔL_n being the increment of length in the stay, the value of this strain can be calculated as presented in Eq. (1).

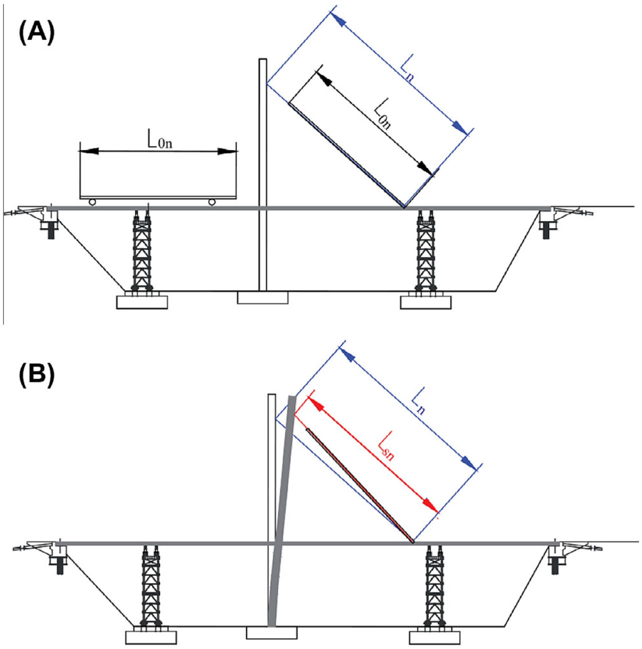

Fig. 1. Definition of the different lengths of a stay: (A) Installation of the first stay, with a length L_{0n}, on site in the un-deformed geometry, L_n. (B) Stressed length, L_{sn}, when the stay is elongated and length L_n. Unfilled pylon shows the un-deformed geometry and filled pylon the deformed one when the stay is installed and stressed.