A new concept of overhead movable scaffolding system for bridge construction

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Summary

In the last decade, a research and development process, initiated in the Faculty of Engineering of the University of Porto has brought out an innovative technology for bridge construction: *Organic Prestressing*. This new technology is now being applied to a brand new generation of movable scaffolding systems.

The present paper presents a new concept of overhead movable scaffolding systems for in situ bridge construction, in which the scaffolding structure is similar to a "bowstring", with the particularity of having an arched upper chord and an actively controlled lower chord.

Keywords: Organic Prestressing; Bridge Construction; Movable Scaffolding Systems; Deflection Control.

1. Introduction

Advantages of organic prestressing application in structures with high "live load / dead load" ratios and with relatively "slow" loadings, such as movable scaffolding systems used for bridge construction [1], has promoted an increasing development of this technology in the past few years.

Inspired on the behaviour of nature structures (biomimetics), more specifically in the muscle behaviour, Organic Prestressing System (OPS) is an automatically adaptive prestressing system which has the ability to increase or decrease prestressing forces according to live load variation. It is no more than a prestressing system in which the tension applied is automatically adjusted to the actuating loads, through a control system, in order to reduce the structural deformations and minimize tensions.

The first movable scaffolding system with OPS was designed for the construction of the Rio Sousa highway bridge in northern Portugal, a double deck comprising 15x30 m long spans [2]. The scaffolding steel structure comprises four independent main girders (see Fig. 1), brackets, friction collars and bogies sets. It is strengthened with an OPS equipment, which essentially consists of unbonded prestressing cables, anchorages, deviation shores and saddles, hydraulic actuators (see Fig. 2), sensors and automation components.

Fig. 1 *First OPS movable scaffolding system application*

Fig. 2 *Actuator and Organic Anchorage*

The application of OPS allows for lighter and more functional structures. The maximization of its potential, whose limits are yet to be established, justifies the design of new types of steel scaffolding structures, congregating structural advantages and responses to functional needs, especially of kinematic nature.

A new concept of movable scaffolding system for *in situ* bridge construction is presented, namely, an overhead equipment in which the scaffolding structure is similar to a “bowstring”, with the particularity of having an arched upper chord and an actively controlled lower chord.

This paper performs an overall presentation of the main concept, including a description of the superior girder and of the transverse structures which sustain the formwork and an analysis of their kinematics, comprising simultaneously structural features and formwork engineering related issues. Special attention is given to the OPS system and inherent control strategy.

2. Superior Girder

The equipment presented in Fig. 3 is an overhead movable scaffolding system conceived to build cast *in situ* concrete bridge decks with a maximum span of 50 m. The superior girder is a steel structure similar to a “bowstring”, with an arched upper chord and a lower chord actively controlled by an Organic Prestressing System (OPS) during the concrete pouring and deck prestressing stages.

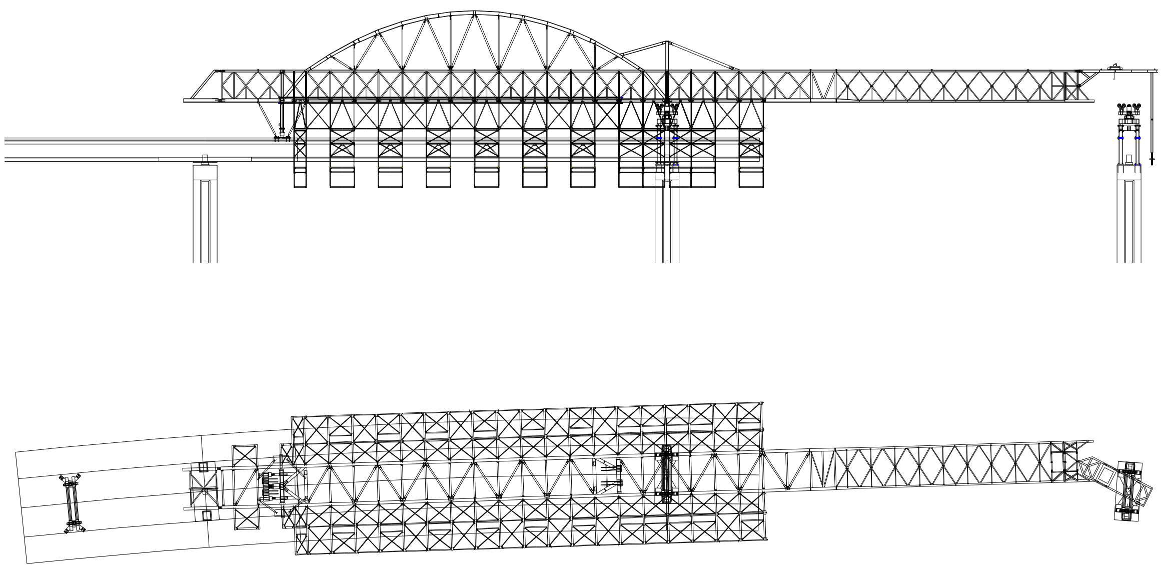

Fig. 3 *Elevation (top) and plan view (bottom) of an overhead movable scaffolding system strengthened with OPS*

2.1 Superior Girder steel structure

The steel structure of the superior girder comprises the following main components: arch, main girder, upper tie, front nose, front crane and rear nose.

The steel arch, with a maximum height of 9 m and a maximum distance between supports of 40 m, is an HEB 400 profile that diverges into 2 HEB 300 in the abutments.

The main girder – a modular truss with a transversal section of 4.00m x 3.00m – has a total length of 60 m, of which 40 m are suspended from the arch, 15 m form the front cantilever and the remaining 5 m constitute an extraordinarily short rear cantilever. Its main purpose is to suspend the transversal structures that support the formwork. The main girder inferior chords are actively controlled by an OPS system between the arch abutments, retaining abutments displacements and subsequent arch opening. This particularity allows the structure to behave like a "bowstring" during the concrete pouring stage.

The arch and active tie structural efficiency allows a drastic reduction of the main girder deformations between supports during the concrete pouring stage, with a maximum mid-span vertical deflection inferior to L/2000 (approximately 2.5 cm). The cantilever concrete pouring extension (1/5 of the following span) is not controlled by OPS. The cantilever deflections are reasonably restricted through inclusion of two superior passive ties with a maximum eccentricity of 6 m in the pier support section relative to the girder inferior chord, resulting in a considerable stiffness increase.

The feasibility of the equipment launching is guaranteed by the front nose, the front crane and the rear nose. The front nose has a total length of 27.5 m and a triangular transversal section with a height of 3 m and a width of 4 m.

The rear nose consists on a prolongation of the main girder, formed by two vertical plane trusses with capacity to open (through independent rotation around a vertical axis), enabling the rear pier frame disassembling with the movable scaffolding structure in the concrete pouring position.

On the other hand, the front crane consists of a rotatory nose prolongation equipped with a temporary frame and an elevation winch. With the structure still in the concrete pouring position, the temporary frame "lands" on the front pier (by means of hydraulic jacks) allowing the front crane to elevate, from the ground, and to assemble the previously dismounted pier frame.

2.2 OPS system

OPS is nothing more than an active control prestressing system [3] whose objective is to reduce deformations and/or tensions due to live loads. The main elements (see Fig. 4) are the actuator in the organic anchorage, the unbonded cables, the sensors and the electronic controller in the girder control unit [4], [5], [6], [7].

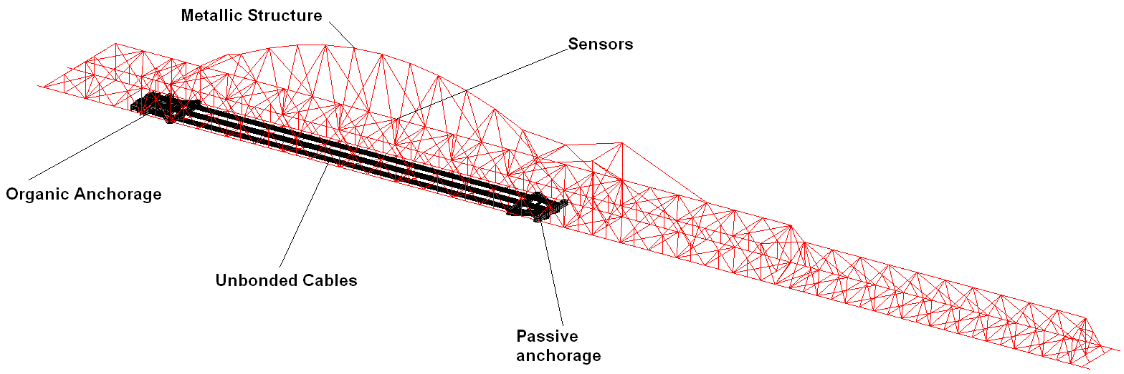

Fig. 4 *3D scheme of an Overhead MSS girder equipped with OPS*

The control strategy is similar to the first OPS applications, adopting the mid-span vertical deflection as primordial control variable. To implement this technique, a reservoir is fitted in a fixed location near a pier, and pressure sensors are spread along the structure, connected by a fluid circuit (Fig.5a). Main girder deflection variation can be determined through changes in hydrostatic pressure [6], [7]. The sensors transmit the information to an automaton which processes it according to a control algorithm, and then "decides" between maintaining or changing the prestressing force [1]. Typically, in a concrete pouring situation, the *concrete pouring mode* is turned on and if the mid-span deflection exceeds a pre-defined limit, the automaton "decides" to increase the hydraulic jack (actuator) stroke, moving the organic anchorage beam (see Fig. 2) and simultaneously tensioning four rectilinear prestressing cables.

In simplified mathematical terms, during the concrete pouring stage, the control algorithm is mainly stated by expressions in Eq. (1):

$$\begin{cases} \overline{\Delta}(t_i) > \Delta c & \Rightarrow \quad nc(t_i + \Delta t) = nc(t_i) + 1 \times \xi(t_i) \\ \overline{\Delta}(t_i) \leq \Delta c & \Rightarrow \quad nc(t_i + \Delta t) = nc(t_i) \end{cases} \qquad (1)$$

where,

$\overline{\Delta}(t_i)$ is the filtered mid-span deflection at instant t_i;

Δc is the predefined mid-span deflection control limit;

Δt is the time step adopted in the control algorithm $(\Delta t = t_i - t_{i-1})$;

$nc(t_i)$ is the number of stroke unit-step changes performed by the actuator at instant t_i;

$\xi(t_i)$ is the overall validation function at instant t_i (assumes values 0 or 1) [8].

The symmetric algorithm controls the bridge deck prestressing stage (reverse process). In both stages, software filters are used to overlook vibrations. Indeed, this control algorithm is valid for static control, thus, to avoid control instability, unit-step changes performed by the actuator (output) must not depend on vibrations.

Software safety features provide continuous evaluation of the hardware components integrity state and of the whole system operational state. If this continuous evaluation suggests any abnormal situation, OPS reaches a breaking level (actuator blockage) and an alarm is triggered [9]. To achieve this fundamental principle, software codes are developed according to Eq. (1), where any unit-step change is multiplied by an overall validation function $\xi(t_i)$ which establishes, at any instant t_i, if all OPS subsystems and components verify simultaneously operational and integrity predefined criteria ($\xi(t_i)=1$) or not ($\xi(t_i)=0$).

OPS commands allow the operator to choose the desired operational mode, according to each construction stage. The control software is computed by a Programmable Logic Controller (PLC) located in the girder control unit (Fig. 5b, c).

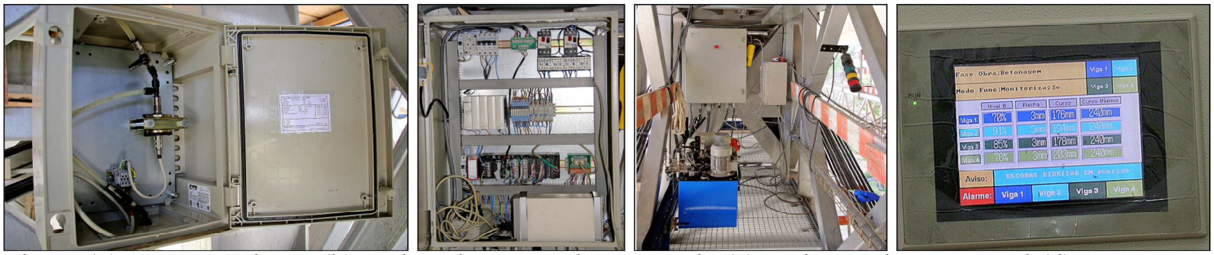

Fig. 5 *(a) Sensor Cabinet (b) and girder control unit inside (c) and outside views and (d) HMI*

Through a Human-machine interface (HMI) (Fig. 5d) the operator is permanently informed about the state of the system. It displays, among other information, the girder deflection, warnings and alarms. Fundamental data is continuously recorded for subsequent analysis.

3. Transversal structure

An overhead movable scaffolding system constructs the bridge's deck beneath the main girder. Therefore, the transversal structure that supports the formwork is suspended from the main girder by means of "transversal grips" that guarantee the required width for the formwork. The transversal structure is materialized by two pairs of steel trusses, each of them constituted by a horizontal and a vertical truss.

During the concrete pouring stage, the horizontal trusses are interconnected in order to position the formwork. During this stage, the high level of loading and deformation requirements imply the installation of a pair of high strength steel threadbars in an inner position, suspending the transversal structure and reducing its span (see Fig.6). The threadbars are conveniently positioned to facilitate the placing of the prefabricated deck steel reinforcement.

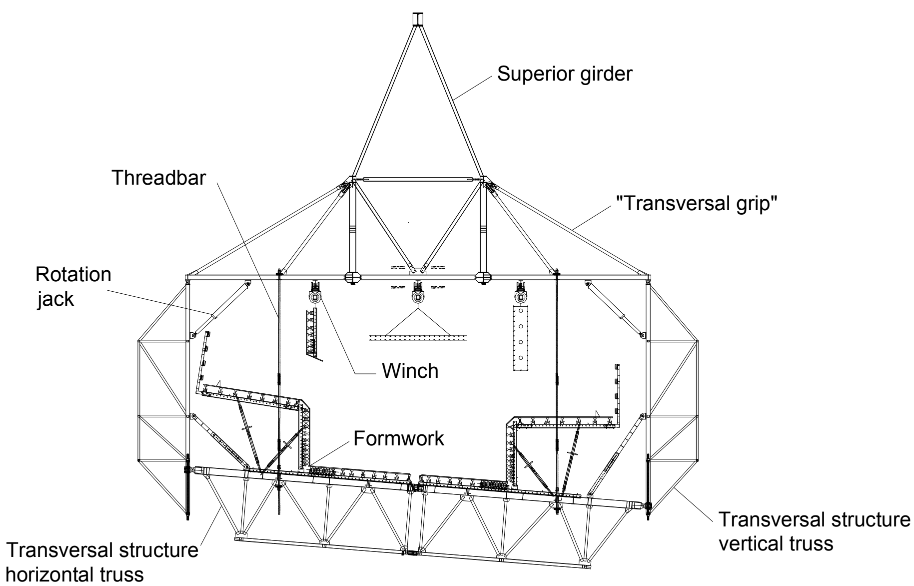

Fig. 6 *Movable scaffolding system in concrete pouring position (cross section)*

Before the launching stage, the girders are lowered to free all formwork from the deck, the horizontal trusses are disconnected, the steel threadbars are disassembled and the transversal structures are opened. The opening motion is performed actuating on hydraulic jacks, allowing the automatic rotation of transversal structures and formwork.

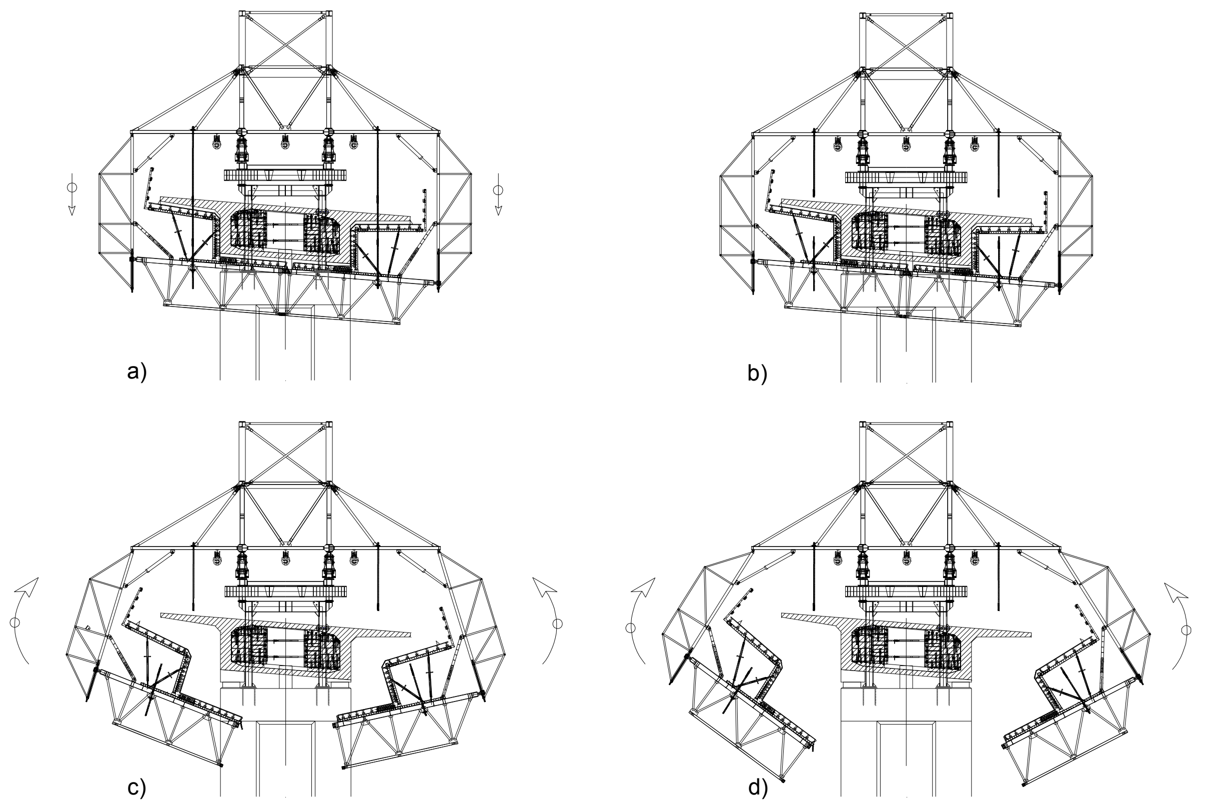

Fig. 7 *Girder descending, threadbars disassembling and transversal structures rotation*

The transversal structures were conceived to construct bridge and viaduct decks with a maximum longitudinal slope of 5% and variable transversal slope up to a maximum of 8%. Unlike the traditional scaffolding systems, in which the deck is constructed in a straight line between piers, this transversal structure allows the construction of a polygonal with 5 m long segments, obtaining a better approximation to the directrix shape (circular or clothoid).

The “transversal grips” support pairs of winches (see Fig. 6), making it possible to transport the pre-fabricated steel reinforcement and prestressing cables ducts directly from the lorry to the construction front, with no need for auxiliary elevation equipment.

4. Formwork

The formwork of movable scaffolding systems is, in general, specifically conceived for each application. The first application of the present equipment was developed for the construction of a box cross section concrete deck, 11.50 m wide and with a constant height of 2.40 m. It was assumed that the concrete pouring was to be carried out in two different stages: the first stage comprises the construction of the bottom slab and vertical walls and the second stage comprises the construction of the top slab, cantilevers included (see Fig. 8). In order to avoid the appearance of cracks in the first stage concrete (mainly in the vertical walls) the scaffolding structure mustn´t experiment significant deformations during the second concrete pouring stage. The inclusion of an OPS system is synonym of deflection control and a guarantee of low deformations.

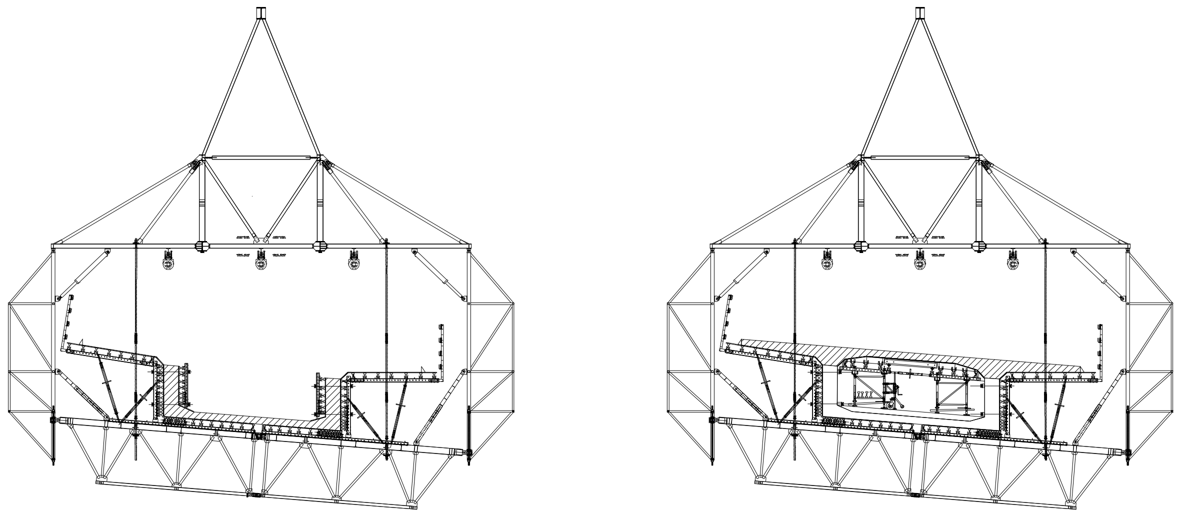

Fig. 8 *Formwork and concrete pouring stages: 1st stage (left) and 2nd stage (right)*

The formwork design process considered several peculiar features related with the movable scaffolding system geometry and kinematics. A formwork "table", with a length of 5 m and a longitudinal distance between support alignments of 2.80 m, was achieved. The bottom external formwork is divided in two symmetric parts, in order to make the transversal structures opening motion viable. The supports are materialized by 6 points of vertical contact and 2 points of horizontal contact (fundamental throughout the opening motion) with each transversal structure.

The formwork was developed aiming at functionality, being noteworthy the connection between the bottom and the lateral external panel which allows vertical and transversal adjustments as well as the formwork "table" adaptability to the deck geometry. In addition, the top slab formwork is launched to the following span by its own means.

Conclusions

The conjugation of OPS technology with the structural efficiency of an arch resulted in an active "bowstring" steel structure, allowing the achievement of an extremely light and functional movable scaffolding system. The following advantages standout, in comparison with a traditional equipment:

- Reduction of the equipment weight (25 to 30% of steel volume);
- Reduction of the acquisition costs (about 15%);
- Reduction of operational costs (10 to 20%);
- Mid-span deflection control and ability to program pre-cambers;
- Continuous monitoring of the scaffolding structure, enabling higher safety levels;
- Easier transportation and on site assemblage of the scaffolding equipment;
- Simplicity of steel connections (maximum tensions substantially reduced).

Moreover, implementation of OPS technology in movable scaffolding systems and, particularly, in the present equipment, enables the construction of high speed railways bridge decks, which are substantially heavier (about 30%) than both common railway bridge decks and highway bridge decks.

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