# A Scaffolding System strengthened with Organic Prestressing – the first of a new Generation of Structures

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## Summary

The first full scale application of a movable scaffolding system strengthened with an organic prestressing system (OPS) is briefly described. The main characteristics of the steel structure and of the OPS technology are presented and significant aspects of the equipment's structural behaviour are given. The advantages of this innovative solution are established. Results prove that this control system enables the design of lighter scaffolding systems, reducing their service deflection at the same time.

**Keywords:** organic prestressing system (OPS); movable scaffolding system; biomimetics; prestressing; static control; bridge construction.

## Introduction

About 50 years ago, Freyssinet and Zetlin mentioned the possibility of strengthening structures with *active cables* (according to Falcó[1]). They did not continue studies in this field probably because the technological context then was unhelpful. After 1970, several applications on active control of structures involving *active cables* were developed.[2,3] In these solutions *active cables* were regarded as complementary structural elements used to reduce vibrations (dynamic control) and not as fundamental structural elements permanently involved in structural behaviour, for service and ultimate loads.

The innovative structural solution presented in this paper is the result of a research and development process initiated in 1994 by the Faculty of Engineering of the University of Porto. Typical scientific main stages were followed: fundamental research,[4–6] numerical analysis,[7–10] experimental tests.[11] More recently a full scale application was implemented (*Fig. 1*).

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Organic prestressing system (OPS) is a concept inspired by the behaviour of an *organic structure* found in nature: the muscle.[4-6] It is nothing more than an active control prestressing system, whose objective is to reduce deformations and/or stresses due to live loading. Although additional measures are taken to ensure reliability, OPS involves a simpler algorithm than those necessary for other active control applications,[2,12] since it is conceived for static control applications.

Numerical studies of different OPS applications on civil engineering structures reveal that OPS can be very advantageous for structures with high "live-load/dead-load" ratios.[8] Scaffolding systems are a good example of such structures. Calculations show that this technology can substantially reduce prestressing losses and well known unfavourable effects of conventional prestressing.[4,5,11] Experimental tests in the laboratory and at the site confirmed OPS technology feasibility and proved the accuracy of previous numerical analysis results.[11] In 2005, the first full scale prototype was implemented in a bridge construction process in northern Portugal. A very light and functional movable scaffolding system was achieved (steel weight ≈ 17 kN/m).

The main structural advantages of OPS are simple to identify. Regarding *Fig. 2,* if prestressing (P) is simultaneously applied with service loads (G + Q), the beam with main span L assumes a structural behaviour similar to a continuous beam with three times L/3 long span. Deflections and bending moments are substantially reduced. If conventional prestressing was applied (previously) on the "empty structure", undesirable behaviour would occur – the prestressing (P) effect would be,

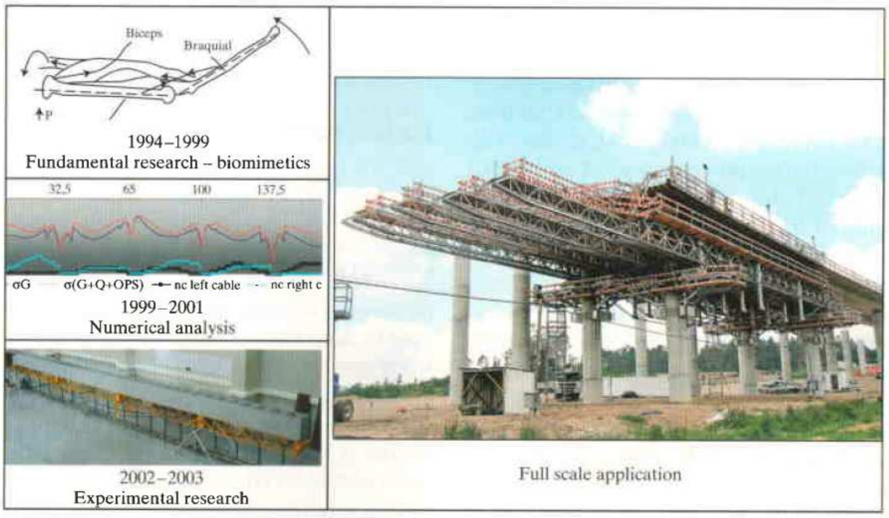



*Fig. 1: OPS research program – main stages*

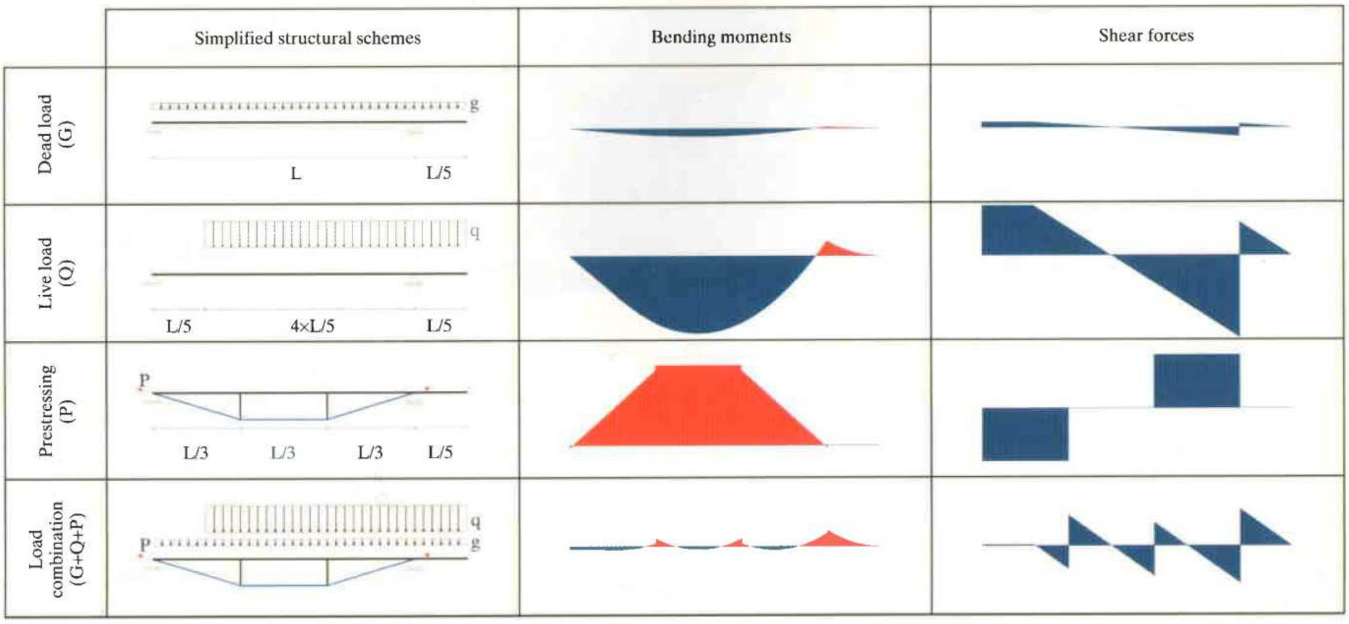



*Fig. 2: Qualitative draw of OPS main structural effects on a scaffolding structure*

by itself, nearly as much adverse as the live load (Q) effect.

This paper gives a brief description of the first movable scaffolding system strengthened with OPS. Special attention is given to the concrete pouring stage, where OPS is most useful. Kinematics, formworks and other similar conventional equipment aspects are merely superficially mentioned.

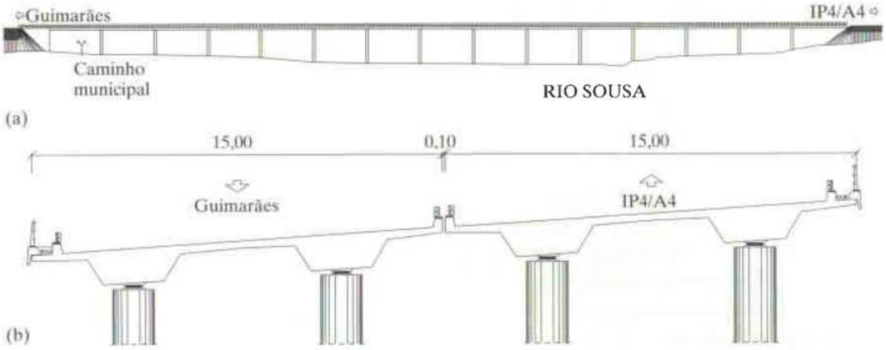



*Fig. 3: (a) Elevation (b) and cross section of Rio Sousa Bridge*[13] *(Units: m)*

## Rio Sousa Bridge

The first OPS movable scaffolding system was designed for the construction of the Rio Sousa highway bridge (Portugal). The bridge includes two common prestressed concrete decks, both comprising 15 × 30 m long spans (*Fig. 3*). Minimum plant curvature radius is not particularly small ($r$ = 1000 m). The longitudinal beam height is 1,25 m and each deck weighs approximately 235 kN/m.

The bridge geometry simplicity was regarded as one of the most important requirements to implement this first full scale application, so kinematics would not imply particular difficulties.

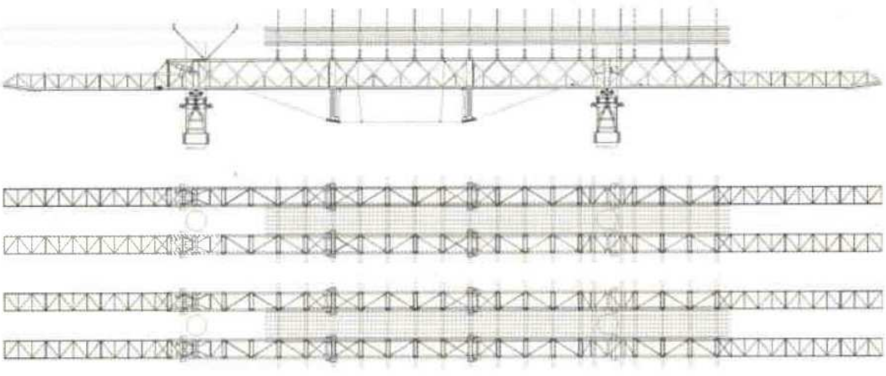


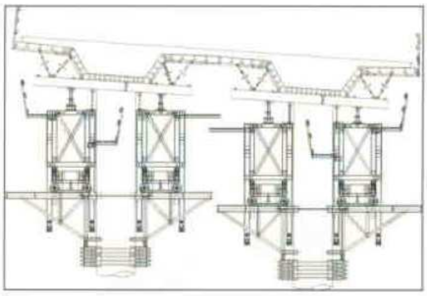
*Fig. 4: Elevation and plant view of OPS movable scaffolding system*[14]

## Main Elements of the Steel Structure

The presented equipment is an underslung movable scaffolding system with a total length of 64 m (*Figs. 4* and *5*). The "main body" length is 40 m and both *launching noses* are 12 m long. The principal loading extension (concrete pouring) is $L$ = 30 m and "starts" at L/5 = 6 m from the back support (left pier – *Fig. 4*).

The steel structure comprises four main girders (*Figs. 4* and *5*) and four sets of brackets and bogies (similar to other known equipment). Two complementary sets of brackets and bogies are also part of the equipment and are set up in the following "new" support to "receive" the main girders during the launching stage. Each girder is reinforced with two sets of actively controlled prestressing cables.

The main girders are modular trusses. Their transversal section (1,25 m × 2,00 m) was designed for easy transportation and on site assemblage. The steel weight of the four main girders is approximately 1080 kN. According to numerical studies, to achieve a similar conventional solution, an additional 30% of structural steel is needed.[10]



(a)

(b)

*Fig. 5 (a, b): Section and front view of the bridge and of the OPS movable scaffolding system*

Moreover, any conventional solution is unlikely to achieve such a high performance of deflection limitation.

## Organic Prestressing System – OPS

OPS involves known technologies.[5,11] The main elements are (1) the actuator in the *organic anchorage*, (2) the unbonded cables, (3) the sensors and (4) the electronic controller in the girder control unit (*Fig. 6*). All of them have been used before with reliable results, but not in the present combination.[15]

A very simple control strategy was first developed for simply supported beams.[4] It was not found adequate to use sophisticated standard control tools[1-3, 12] due to the simplicity of the control problem. An effective control system was achieved, where the main objective was to ensure no tension (or even low compression) at predefined control cross sections.[4,7] Afterwards, a similar algorithm was developed using mid-span deflection as main control variable (input).[9,11,16,17] In simplified mathematical terms, the latest algorithm – in concrete pouring stage – is mainly stated by expressions in Eq. (1):

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

where,

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

$\Delta c$ is the predefined mid-span deflection control limit;

$\Delta t$ 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).[16]

The symmetric algorithm controls the bridge deck prestressing stage (reverse process). In both stages software filters are used to oversee vibrations (*Fig. 7*). 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. More than one technique may be used to achieve such a filtering procedure. One solution consists of defining $\bar{\Delta}(t_i)$ as the computed average of a convenient number of consecutive mid-span deflection measures, during an adequate analysis period.

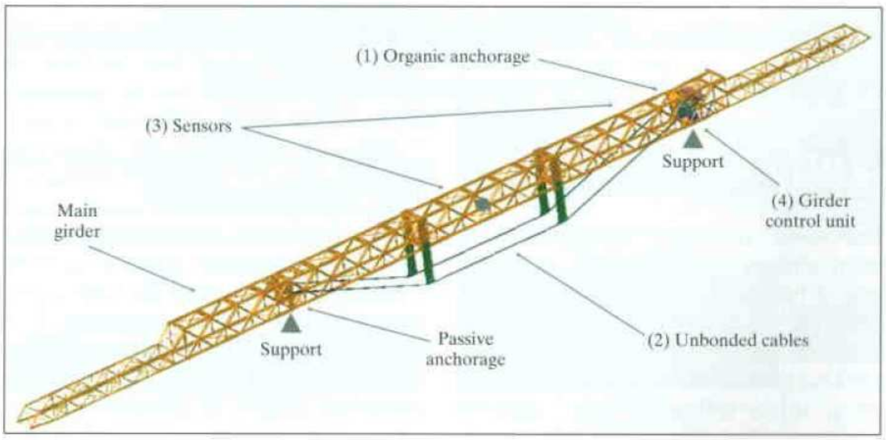



*Fig. 6: 3D scheme of one OPS movable scaffolding system main girder[9]*

Software safety features provide continuous evaluation of the integrity state of the hardware components and of the operational state of the whole system. If this continuous evaluation suggests any abnormal situation, OPS reaches a breaking level (actuator blockage) and an alarm is triggered. To achieve this fundamental principle, software codes were developed according to expressions in 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 ($\xi(t_i) = 0$).

### *Sensors and Control System*

The mid-span deflection is measured by means of sensors (pressure transducers). 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 (*Figs. 8* and *9a*). Main girder deflection variation (dH) can be determined through changes in hydrostatic pressure.[9,11]

Before the Rio Sousa Bridge construction started, data was recorded for several weeks in different atmospheric conditions. The system accuracy was found adequate and its precision was high (±1 mm). The validation of *mid-span deflection measuring system* was one of the most critical issues.

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 each girder control unit (*Fig. 9b, c*).

Through a human-machine interface (HMI) (*Fig. 9d*) the operator is constantly informed about the state of the system. It displays, among other information, the deflection of each girder, warnings and alarms. Fundamental data is continuously recorded for subsequent analysis (*Fig. 7*).

### *Cables, Organic Anchorages and Safety Devices*

Two prestressing cables are installed in vertical planes externally to each box girder (*Fig. 10*). The prestressing cables with a tri-linear configuration are anchored next to the support sections. Angles are imposed by two deviation shores, which divide the span

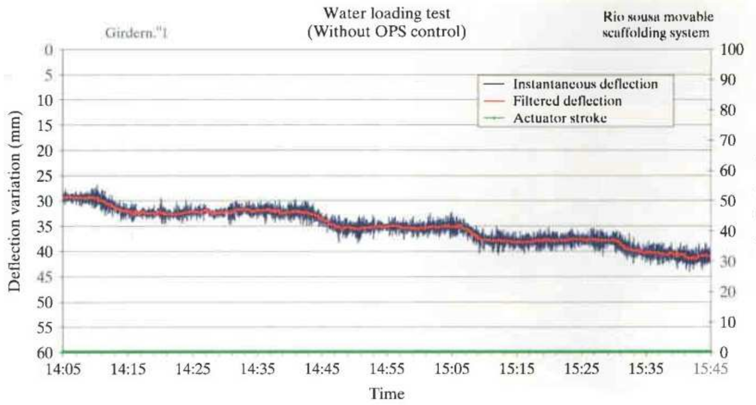



*Fig. 7: Instantaneous and filtered mid-span deflection clip of recorded data during a water test without OPS control*

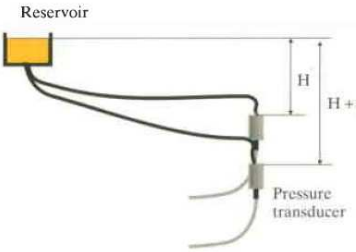



*Fig. 8: Static column fluid pressure measurement*[9]

(L) in three times L/3 long span. Each prestressing cable is composed of a set of 12 monostrands.

Each *organic anchorage* includes a transversal beam (*Fig. 11a*) which allows the simultaneous tensioning of the two cables with only one hydraulic jack (actuator). Cable anchorages are provided via rectangular "anchorage heads", which receive extrusion blocks placed at the monostrand ends.

OPS hydraulic jacks are similar to the ones used in other applications of Civil Engineering. For safety reasons, their maximum stroke is limited, through pressure relief valves and through software control safety codes, causing the OPS actuator blockage (if necessary). If an actuator breaks down, during the loading stage, two large screws with nuts hold the anchorage beam, preventing a decrease of prestressing force in the cables (*safety prestressing retaining system*). Each passive anchorage comprises a pair of rectangular "anchorage heads" which are set up on a steel beam attached to the structure (*Fig. 11b*).

The deviation shores are rectangular tubular cross-sections (RHS profiles) that impose prestressing cable deviation and transmit deviation forces to the steel structure (*Fig. 12a*).[14] These components are equipped with a rotation system, in order to avoid collision with the brackets (set in the piers) during the launching stage (*Fig. 12b*).

The deviation saddles are elements located in the lower extremity of the deviation shores (*Fig. 13*). In order to reduce the strand ducts fretting fatigue damaging, the saddle surfaces (in contact with the strands ducts) are coated with Polytetrafluoroethylene (PTFE).

## Structural Design Additional Issues

This kind of structural design must comprise additional load combinations. The authors suggest that in the near future, an additional accidental combination with OPS failure is considered. Although passive response of OPS cables is considered, present experience is able to verify that such a combination was conditioning for the design of some steel members. Moreover, it should be noted that common load combinations, comprising overload and underload prestressing values, are influenced by the effect of pressure valve insertion in the hydraulic circuit.

Besides specific design criteria, calculation and manufacturing particular aspects are to be observed as in *Table 1*.

In the present application, none of the particular aspects mentioned represented any kind of unexpected difficulty and the particular case of the bolted connections clearly became a major advantage.

## Main Technical Data/Structural Behaviour

An *organic structure* is characterised by parameters which involve power, "evolutionary loadings", or response delays, always in a quasi-static perspective. Here, these are not merely "mechanical parameters" or "control parameters" – indeed they are all structural parameters, as they have a direct influence on the structural design. For example, the actuator speed during concrete pouring ($v_{act}$), which depends on the hydraulic group power, may influence the main girder profile sections – more details of *organic structure* design are given in references.[5,14] Most significant technical data and main *parameterised values* (used for software parameterisation) are presented in *Table 2*.

One of the main characteristics of OPS is the fact that software parameterisation only influences control limits (warnings, alarms and breaking levels), and not the control actions, i.e. OPS does not comprise a model-based algorithm. Thus, even if there are significant

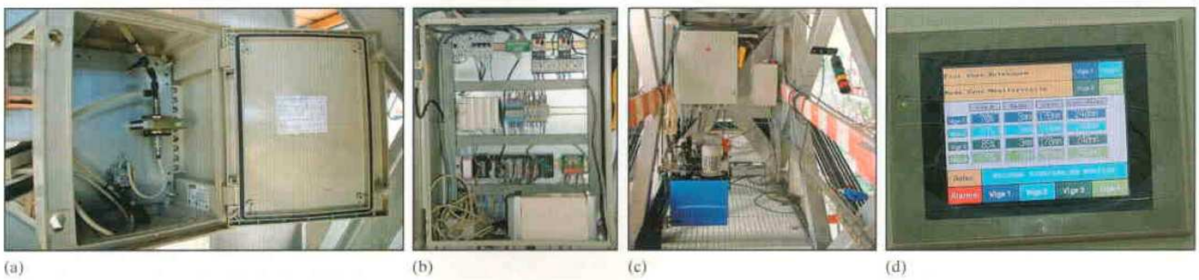



*Fig. 9: (a) Sensor cabinet (b) and girder control unit inside (c) and outside (d) views and human-machine interface (HMI)*

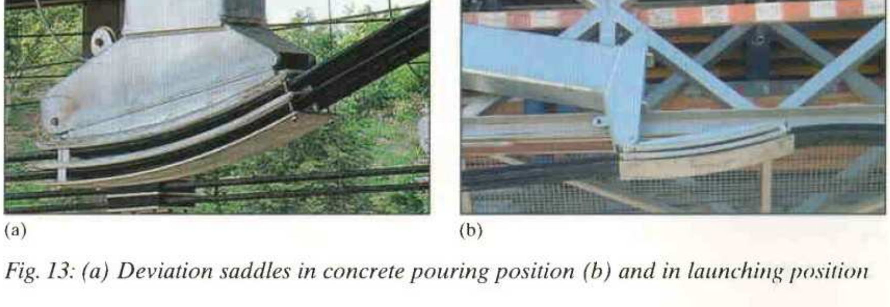
*Fig. 10: OPS cables layout – side view*

(a) (b)

*Fig. 11(a) Organic anchorage with its actuator (b) and passive anchorage*

(a) (b)

*Fig. 12: (a) Cables and deviation shores in concrete pouring position (b) and in launching position*



(a) (b)

*Fig. 13: (a) Deviation saddles in concrete pouring position (b) and in launching position*

uncertainties on stiffness calculation (or other quantities) structural performance may still be adequate. Moreover, if the deflection measuring system calibration is correct (and no integrity problems occur), OPS always tends to reduce deformation, which is generally favourable.

Concerning stress evaluation, no experimental measures were taken. According to numerical models, expressive reductions occur due to OPS action (*Fig. 14*). In the upper chord, moderate compressions result from axial prestressing efforts (OPS almost ensures null compression due to flexion effect) and predicted reduction is nearly 60%. In the lower chord, there is a more significant difference because tension turns into compression and absolute predicted reduction is about 40%. It is clear that OPS enables a significant load capacity increment.

According to numerical models, the predicted mid-span deflection with OPS (static value) is 2,5 mm (*Fig. 15*). That represents a huge reduction when compared with the corresponding value without prestressing cables (120,0 mm). It should be noted that if the same structure was implemented with passive (conventional) prestressing cables installed, i.e. without OPS control, expected mid-span deflection would still be 64,0 mm – which means that OPS results in a 96% mid-span deflection reduction.

Experimentally measured values (*Fig. 15*) reasonably confirm numerical prediction and show two effects which are to be analysed.

- During concrete pouring, vibrations occur due to slight dynamic actions related to concrete pouring tasks. These vibrations are characterised by typical maximum amplitudes of 10 mm and are greater than permanent ambiental vibration amplitudes (typically 1 mm).
- Furthermore, if the pouring procedure is fast (more than 2 $m^3$/minute), a slight delay may be observed – quasi-static deflection may be nearly 4 mm – in a transitory period. Nevertheless, approximately 2 min after each concrete pouring increment, quasi-static deflection becomes almost coincident with predicted value (2,5 mm). The relevant mid-span deflection value may be regarded as 2,5 mm and that remains valid for all the concrete pouring period.

| Issue | | Description |
|---|---|---|
| Phenomena of increasing importance | 1) Global buckling | Attending to the slenderness of the girders (≈50) and to axial force importance, a study of global buckling was performed. Cables are a stabilizing factor for this particular phenomenon. |
| | 2) Cable fatigue | Current fatigue normative documents do not consider load cases characterised by large stress variations and low number of cycles. Maximum stress amplitude was limited to 50% of prestressing steel ultimate limit strength. |
| Conception and design of new structural elements | 3) *Organic anchorage* | The design of organic anchorages and main girders must include transitory global torsion effects caused by eventual rupture of one monostrand or caused by eventual differences in cables average lengths. |
| | 4) Deviation shores and deviation saddles | Deviation shores and deviation saddles assume different behaviours along each cycle. Transition between stages is achieved without performing any pined or bolted connection, safeguarding safety and functional simplicity (*Fig. 12*). |
| Uncommon design detailing | 5) Front supports | During the concrete pouring stage, the structure is longitudinally fixed to the previously constructed deck near the rear vertical support. Therefore, frontal support must accommodate axial deformation, imposed on the structure by prestressing forces. |
| | 6) Bolted connections | The bolted connections are extremely light due to stress level on lower chords (*Fig. 14*) and due to shear resistance increasing (prestressing effect). |
| Functionality requirements | 7) Pre-assemblages and preliminary motion tests | Structural elements with particular functionality requirements (kinematical features and/or high precision geometrical demanding) are to be manufactured under special conditions and should be previously tested |

*Table 1: Calculation, detailing and manufacturing particular aspects*

| | Parameter | Description | Value |
|---|---|---|---|
| Current structural data | $L$ | Span (Rio Sousa bridge) | 30,00 ± 0,40 m (V) |
| | $G$ | Dead weight of each girder (including formwork and equipments) | 480 ± 20 kN (V) |
| | $Q/L$ | Concrete load on four girders (global linear weight) | 235 ± 5 kN/m (NV) |
| | $\Delta(G)$ | Mid-span deflection after launching (relaxed cables) | 12 ± 1 mm (V) |
| | $\Delta(G+Q)$ | Mid-span deflection due to dead load and concrete load (without cables) | 120 mm (NV) |
| | $\Delta(G+Q+OPS)$ | Mid-span final deflection after concrete pouring | 2,5 ± 1 mm (V) |
| | $P(G+Q)$ | Maximum service prestressing force in each cable | 960 ± 80 kN (NV) |
| | $f$ | First eigen-frequency of one girder before loading (vertical direction) | 2,88 ± 0,15 Hz (V) |
| | $\Delta P_f$ | Friction prestressing losses at mid-span section | 2,57% ± 0,3% (V) |
| | $\sigma_s$ | Maximum service stress in the steel girder (concrete pouring) | 151 MPa (NV) |
| | $\sigma_p$ | Maximum service stress in the prestressing cables | 580 MPa (NV) |
| Non-current structural data | $TL$ | Load period (concrete pouring) | 25 000 ± 10 000 s (V) |
| | $v_Q$ | Maximum medium mid-span vertical speed due to concrete load | 0,012 mm/s (NV) |
| | $\Delta c$ | Fixed mid-span deflection control limit | 2,5 mm |
| | $\Delta t = t_i - t_{i-1}$ | Time step adopted in the control algorithm | 60 s |
| | $v_{act}$ | Actuator speed (concrete pouring) | 0,23 ± 0,02 mm/s (V) |
| | $\Delta L_{act}$ | Maximum actuator stroke variation during concrete pouring | 90 ± 15 mm (V) |
| | $\Delta_{uw}$; $\Delta_{ua}$ | Parameterised *warning* and *first alarm* upper deflection | 5 mm; 25 mm |
| | $\Delta_{dw}$; $\Delta_{da}$ | Parameterised *warning* and *first alarm* descendent deflection | 5 mm; 30 mm |
| | $P$ | Maximum oil pressure on actuators | 350 ± 20 bar (V) |
| | $t_{min}$; $t_{max}$ | Parameterised acceptable – non-warning – temperature interval limits | 0°C; 40°C |

*Table 2: Resume of technical data (experimentally verified (V) or not (NV))*

## On Service – More Significant Aspects

After a period of approximately 16 + 4 + 2 weeks for (a) manufacturing, (b) on site assemblage and (c) final tests respectively, the equipment started its job. Typically, one-week cycles are implemented, but in the present application 5-days cycles were achieved more than once.

In each cycle, the girders are launched and the formwork is positioned – day 1 (afternoon) and day 2 (morning). If required, during formwork positioning, OPS may be used to implement predefined construction deflections, which does not last more than few minutes. Day 2 (afternoon) and days 3 and 4 are spent setting up deck steel

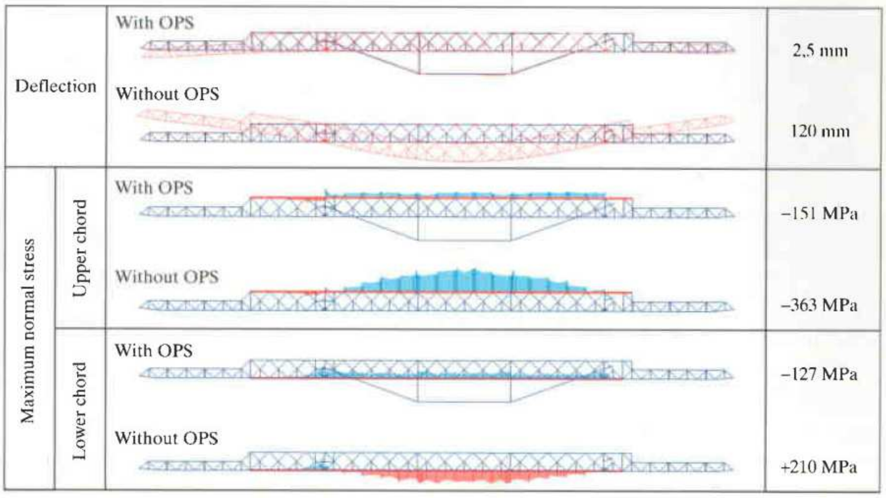



*Fig. 14: Structure response of a model with and without OPS – concrete pouring stage*

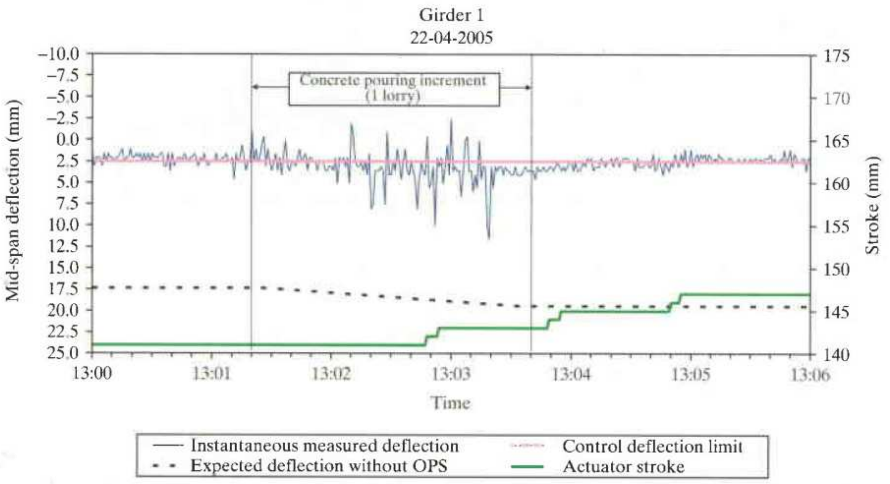



*Fig. 15: Instantaneous recorded data during a concrete pouring operation (6 minutes clip)*

*Fig. 16: General view of on site operations over OPS movable scaffolding system*

and prestressing steel reinforcement (*Fig. 16*). Before the concrete pouring – day 5 – the OPS operator verifies the existence of any kind of warnings. Then the OPS *concrete pouring mode* is selected. After the concrete pouring, OPS is locked. Common cycle ends three days later – day 1 (morning) – with the deck prestressing operation. Reverse (and similar to *concrete pouring mode*) OPS functions are used. Finally, in order to prepare the next launching stage, actuators are totally retracted and deviation shores are turned into launching position.

After four cycles, the contractor's staff was independently in charge of all OPS operations. Indeed, OPS implies no more than four types of quite simple on site operations: (a) Arm/disarm deviation shores, (b) turn on and off OPS according to cycle stage, (c) compare the concrete pouring curve with HMI displayed data (*Fig. 17*); (d) verify warnings and alarms display.

Concrete pouring curves (comprising concrete pouring adopted procedure) were printed out (*Fig. 17*) with acceptable ranges of values (concrete volume versus actuator stroke), thus giving the OPS operator the possibility to identify any problem (in OPS or even in the steel structure). It should be emphasised that, considering this procedure, the state of the steel structure is evaluated in every cycle, reducing the probability of any significant failure.

Besides the identified advantages during common cycles, significant benefits were found on the repositioning operation of the movable scaffolding system for the construction of the Rio Sousa Bridge second deck. In fact, the reduced weight – about 320 kN – of each girder main body (without *launching noses*, but with platforms and all equipments) allowed the use of relatively light lifting equipment for that operation, without the need of the girders being disassembled/assembled (*Fig. 18*).

This equipment was used for the construction of 23 spans. Energy supply failure situations have occurred without causing any disturbance to the process and no technical problems were recorded. The construction was completed 32 days ahead of the schedule.

## Conclusion

This full scale application confirmed that OPS is simple and feasible. The following advantages are confirmed:

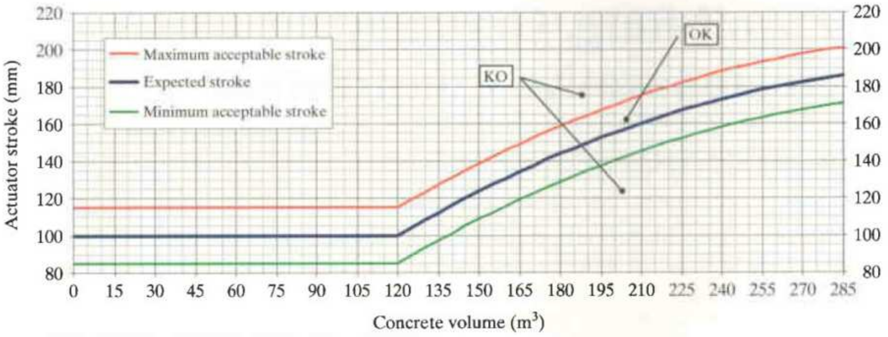



*Fig. 17: Concrete pouring curve used for operational control*

(a) (b)

*Fig. 18 (a, b): Repositioning of the movable scaffolding system for second deck construction*

- Mid-span deflection reduction above 90%.
- Lighter and more functional equipments are achieved (steel quantity reduction about 30%).
- Higher load capacity of equipments is ensured.
- Continuous monitoring of the scaffolding structure enables higher safety levels.
- Ability to programme deflections makes the equipment more efficient.
- Much simpler steel connections are achieved (maximum tensions are substantially reduced).

Moreover, the following indirect advantages are achieved: (a) greater versatility of the scaffolding equipment (may be used for different spans with slight changes); (b) easier transportation; (c) easier on site assemblage of the scaffolding equipment and finally (d) reduction of space needs to store equipment.

Considering all this, there are strong reasons to assert that the presented OPS movable scaffolding system is the first of a new generation of structures.

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