

## First full scale application of a structure strengthened with organic prestressing – A case study

P. Pacheco, A. Guerra, P. Borges & H. Coelho

*Faculty of Engineering & BERD SA (Bridge Engineering Research and Design), Porto, Portugal*

**ABSTRACT:** 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 and consequently making the construction easier and quicker.

### 1 INTRODUCTION

About 50 years ago, Freyssinet and Zetlin mentioned the possibility of strengthening structures with active cables (Falcó et al. 1990). 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 (Soong 1990, Yang & Giaannopoulos 1978). 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, numerical analysis, experimental tests. More recently a full scale application was implemented.

The organic prestressing system (OPS) 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, (Chu et al. 2005) 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 (Pacheco & Fonseca 2002). Scaffolding systems are a good example of such structures. The main structural advantages of OPS

are the control of deflections and reduction of bending moments. If conventional prestressing was applied (previously) to the “empty structure”, undesirable behavior would occur – the prestressing effect would be, by itself, nearly as much adverse as the live load effect.

Experimental tests in the laboratory and at the site confirmed OPS technology feasibility and proved the accuracy of previous numerical analysis results (André et al. 2006). 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  $\approx 17$  kN/m).

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.

### 2 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  $15 \times 30$  m long spans. 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.

### 3 STEEL STRUCTURE

The presented equipment is an underslung movable scaffolding system with a total length of 64 m (Fig. 1). The “main body” length is 40 m and both launching noses are 12 m long.

The steel structure comprises four main girders (Fig. 1). Each girder is reinforced with two sets of actively controlled prestressing cables.

The main girders are modular trusses. 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 (Guerra et al. 2004). Moreover, any conventional solution is unlikely to achieve such a high performance of deflection limitation.

### 4 ORGANIC PRESTRESSING SYSTEM OPS

OPS involves known technologies (Pacheco 1999, André et al. 2006). 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. 2). All of them have been used before with reliable results, but not in the present combination (Pacheco, 2004).

A very simple control strategy was developed. It was not found adequate to use sophisticated standard control tools (Falcó et al. 1990, Soong 1990, Yang & Giaannopoulos 1978, Chu et al. 2005) due to the simplicity of the control problem. The algorithm was developed using mid span deflection as main control variable (input), where the main objective was to ensure no tension (or even low compression) at predefined control cross sections (Coelho et al. 2004, Oliveira 2003, Pacheco et al. 2004, André et al. 2006). In simplified mathematical terms, the algorithm – in concrete pouring stage – is mainly stated by expressions in Eq. (1):

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

where,

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

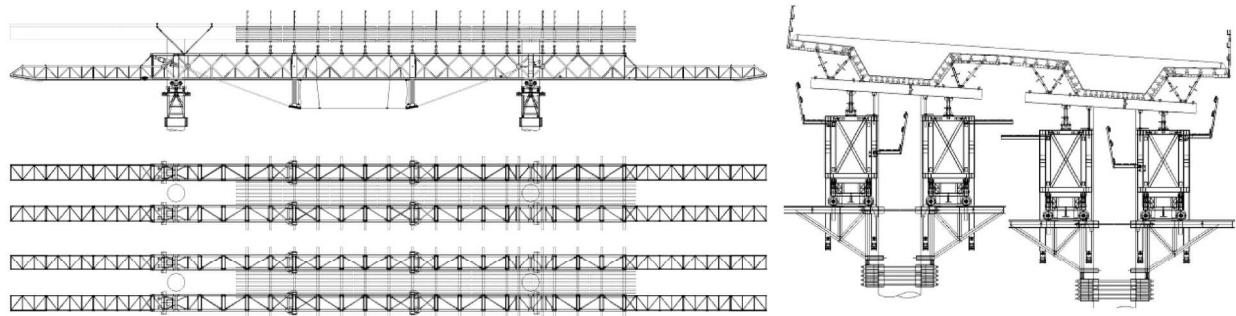


Figure 1. Elevation, plant view and cross section of OPS movable scaffolding system (BERD & AFAssociados 2005).

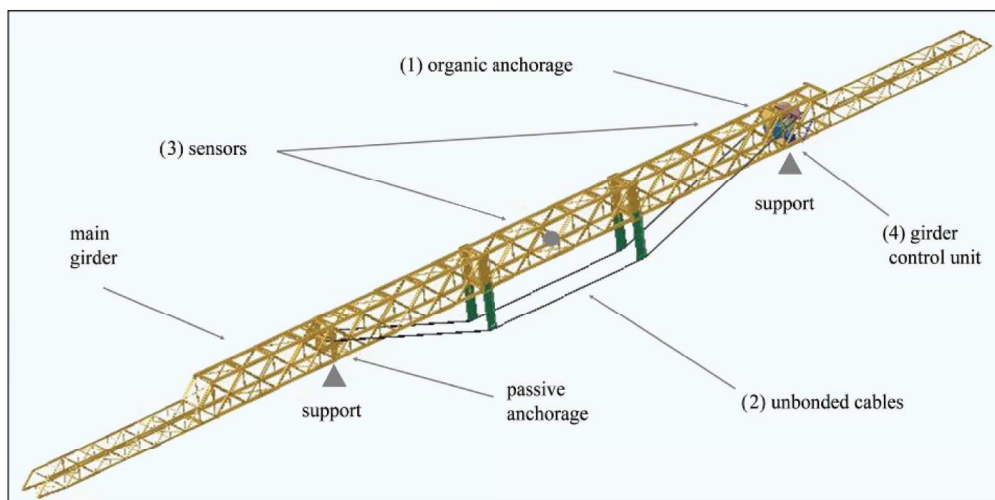


Figure 2. 3D scheme of one OPS movable scaffolding system main girder9.



$\Delta c$  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) (Coelho et al. 2004).

The symmetric algorithm controls the bridge deck prestressing stage (reverse process). In both stages software filters are used to oversee vibrations (Fig. 3). 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.

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 sub-systems and components verify simultaneously operational and integrity predefined criteria ( $\xi(t_i) = 1$ ) or not ( $\xi(t_i) = 0$ ).

#### 4.1 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 (Fig. 4 – left). Main girder deflection variation can be determined through changes in hydrostatic pressure (Pacheco et al. 2004, André et al. 2006) with high precision ( $\pm 1$  mm).

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. 4 – middle).

Through a human machine interface (HMI) (Fig. 4 – right) the operator is constantly informed about the

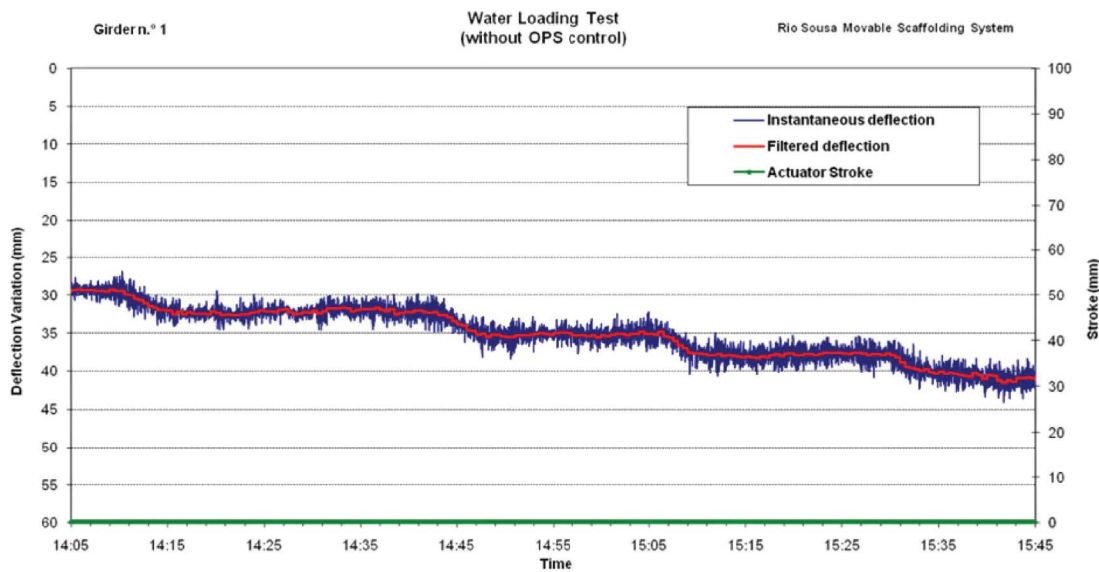


Figure 3. Instantaneous and filtered mid-span deflection (clip of data during a test without OPS control).

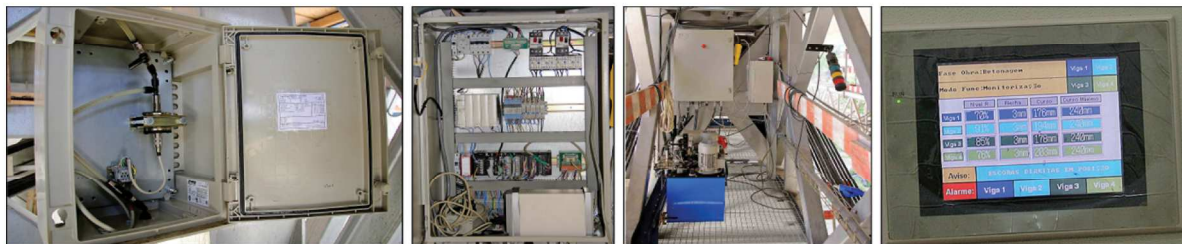


Figure 4. Sensor cabinet (left) and girder control unit inside (middle-left,) and outside (middle right) views and HMI (right).



Figure 5. Organic anchorage with its actuator (left) and passive anchorage (right).



Figure 6. Cables and deviation shores: concrete pouring position (left); launching position (right).

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. 3).

#### 4.2 Cables, anchorages and safety devices

Two prestressing cables are installed in vertical planes externally to each box girder. The prestressing cables (12 monostrands each) with a tri linear configuration are anchored next to the support sections. Angles are imposed by 2 deviation shores, which divide the span ( $L$ ) in  $3 \times L/3$  long span.

Each organic anchorage includes a transversal beam (Fig. 5) 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, 2 large screws with nuts hold the anchorage,

preventing a decrease of prestressing force in the cables (safety prestressing retaining system).

The deviation shores are rectangular tubular cross sections (RHS profiles) that impose prestressing cable deviation and transmit deviation forces to the steel structure (Fig. 6) (BERD & AFAssociados 2005). 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. 6).

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

## 5 STRUCTURAL DESIGN

This kind of structural design must comprise additional load combinations. The authors suggest that an additional accidental combination with OPS failure must be considered. 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.



Table 1. Resume of technical data (experimentally verified (V) or not (NV)).

	Parameter	Description	Value
Current structural data	$L$	Span (Rio Sousa bridge)	$30.00 \pm 0.40$ m (V)
	$G$	Dead weight of each girder (including formwork and equipments)	$480 \pm 20$ kN (V)
	$Q/L$	Concrete load on four girders (global linear weight)	$235 \pm 5$ kN/m (NV)
	$\Delta(G)$	Mid-span deflection after launching (relaxed cables)	$12 \pm 1$ 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	$2.5 \pm 1$ mm (V)
	$P(G + Q)$	Maximum service prestressing force in each cable	$960 \pm 80$ kN (NV)
	$f$	First eigen-frequency of one girder before loading (vertical direction)	$2.88 \pm 0.15$ Hz (V)
	$\Delta P_f$	Friction prestressing losses at mid-span section	$2.57\% \pm 0.3\%$ (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)	$25,000 \pm 10,000$ 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)	$0.23 \pm 0.02$ mm/s (V)
	$\Delta L_{act}$	Maximum actuator stroke variation during concrete pouring	$90 \pm 15$ 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	$350 \pm 20$ bar (V)
	$t_{min}; t_{max}$	Parameterised acceptable – non-warning – temperature interval limits	0°C; 40°C

Besides specific design criteria, calculation detailing and manufacturing particular aspects are to be observed:

- Global buckling;
- Cable fatigue;
- Conception and design of new structural elements (organic anchorages, deviation shores and deviation saddles);
- Uncommon design detailing (front supports compatible with girders axial deformation and extremely light bolted connections);
- Elements with functionality requirements manufactured under special conditions and previously tested.

In the present application, none of the particular aspects mentioned represented any kind of unexpected difficulty.

## 6 TECHNICAL DATA/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. Most significant technical data

and main parameterised values (used for software parameterisation) are presented in Table 1.

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 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. 7). 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. 8). That represents a huge reduction when compared with the corresponding value without prestressing cables (120.0 mm). It should be noted that

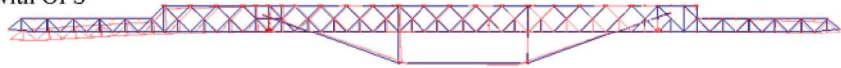

Deflection	with OPS		2,5 mm
	without OPS		120,0 mm
Maximum normal stress	upper chord	with OPS	-151 MPa
	upper chord	without OPS	- 363 MPa
	lower chord	with OPS	-127 MPa
	lower chord	without OPS	+ 210 MPa

Figure 7. Structure response of a model with and without OPS – concrete pouring stage.

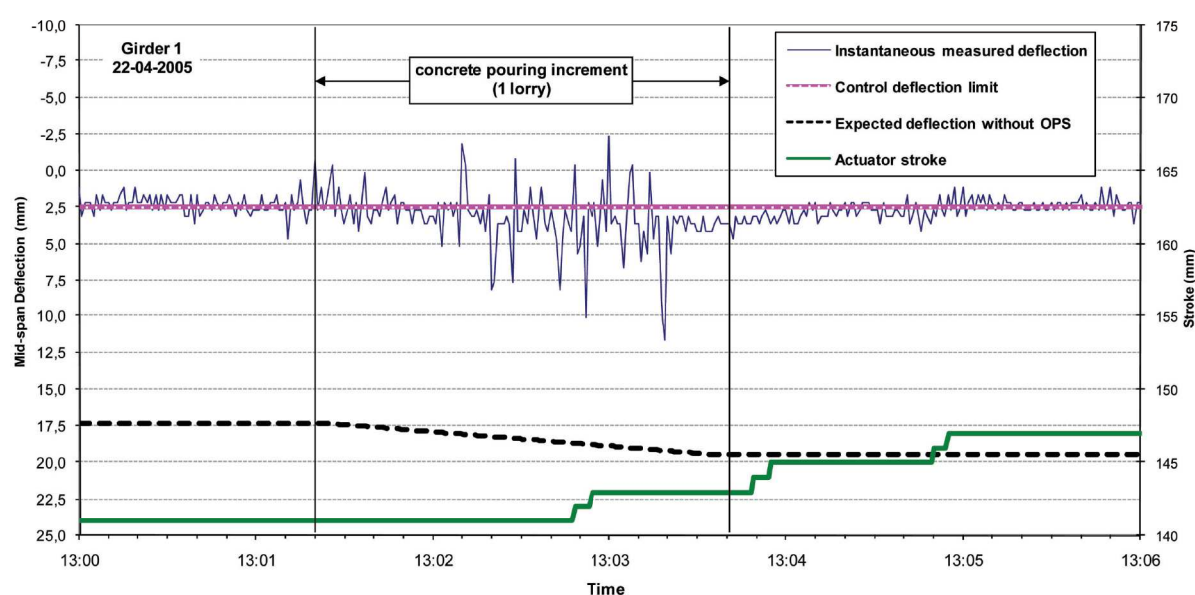


Figure 8. Instantaneous recorded data during a concrete pouring operation (6 min clip).

if the same structure was implemented with 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. 8) 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.

- Furthermore, if the pouring procedure is fast (more than 2 m<sup>3</sup>/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).



Figure 9. General view of on site operations over OPS movable scaffolding system.

## 7 CONCLUSION

This application confirmed that OPS is simple and feasible. Following advantages are confirmed:

- 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.

This equipment was used for the construction of 23 spans in 24 weeks (with two bridge decks).

Considering all this, there are strong reasons to assert that OPS movable scaffolding systems increase the speed of construction.

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