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MOVABLE SCAFFOLDING SYSTEMS STRENGTHENED WITH ORGANIC PRESTRESSING

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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. In this paper, after a brief overview of the first full scale application, different solutions of organically prestressed equipments are synthetically described.*

1 INTRODUCTION

The emergent implementation of organic prestressing technology in bridge construction equipments led to the development of a new generation of movable scaffolding systems for span by span concrete bridge construction.

Organic prestressing system (OPS) is a concept inspired on the behaviour of an organic structure found in nature: the muscle [1,2,3]. It is nothing else than an active control prestressing system, whose objective is to reduce deformations and/or stresses due to live loads.

After a first full scale application, where the feasibility of the organic prestressing system was confirmed and where several advantages were observed, the development of new applications was initiated. The result is a new generation of movable scaffolding systems: lighter, more functional, with increased load capacity and reduced service deflections.

In this paper, and after a brief overview of the first full scale application, different solutions of organically prestressed equipments are described, namely: (a) 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, (b) one overhead equipment, in which an actively controlled cable stayed scaffold structure takes advantage of the load path symmetry to construct two spans simultaneously and (c) one other equipment, an hybrid movable scaffolding system, which enables span by span construction of medium/large span concrete bridges (70 m - 90 m).

For all cases, besides main characteristics description, comprising the steel structure and the OPS implementation, global structural behaviour is analysed. Afterwards, launching stage and kinematics are shortly described, comprising simultaneously structural features and formwork engineering related issues.

2 FIRST FULL SCALE APPLICATION – RIO SOUSA BRIDGE CONSTRUCTION

OPS is a prestressing system in which the tension applied is automatically adjusted to actuating loads, through a control system, in order to reduce structural deformations and minimize tensions.

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 [4]. 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 [1,2,5]. Experimental tests in laboratory and on site confirmed OPS technology feasibility and proved the accuracy of previous numerical analysis results [5]. In 2005, the first full scale prototype was implemented in a bridge construction process in northern Portugal. For that purpose, an underslung movable scaffolding system was developed, comprising four independent steel main girders, brackets, friction collars and bogies sets (Fig. 1). It is strengthened with an OPS system, which essentially comprises unbonded prestressing cables, anchorages, deviation shores and saddles, hydraulic actuators, sensors and automation components.

Figure 1: First OPS movable scaffolding system application

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 4 main girders is approximately 108 ton.

In each girder, 2 prestressing cables are installed in vertical plans externally to the box section. The prestressing cables 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 prestressing cable is composed by a set of 12 monostrands.

Each organic anchorage (Fig. 2 - left) includes a transversal beam which allows the simultaneous tensioning of the 2 cables with only one hydraulic jack (actuator). Cable anchorages are materialised via rectangular “anchorage heads”, which receive extrusion blocks placed at the monostrands ends. Likewise, the passive anchorage (Fig. 2 - right) includes a transversal beam attached to the structure [6].

The deviation shores (Fig. 3 – left) are rectangular tubular cross-sections that impose prestressing cables deviation and transmit deviation forces to the steel structure. These components are equipped with a rotation system, in order to avoid collision with the brackets (set in the piers) during the launching stage. The deviation saddles (Fig. 3 – right) are elements located in the lower extremity of the deviation shores. In order to reduce the strands ducts fretting fatigue damaging, the saddles surfaces (in contact with the strands ducts) are coated with Polytetrafluoroethylene (PTFE).

Figure 2: Organic anchorage with its actuator (left) and passive anchorage (right)

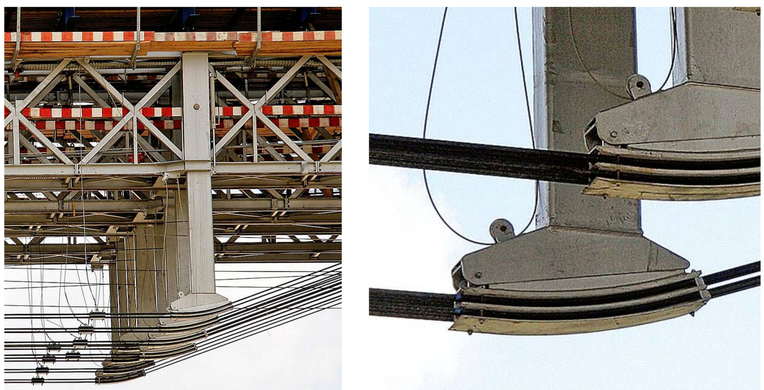

Figure 3: Deviation shores (left) and deviation saddles (right)

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 beam, preventing a decrease of prestressing force in the cables (safety prestressing retaining 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. Main girders deflection variation can be determined through changes in hydrostatic pressure.

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.

Through a human-machine interface (HMI) the operator is permanently 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 [6].

A resume of first OPS movable scaffolding system main functional limits is presented in Table 1.

Table 1 : Main functional limits of first OPS movable scaffolding system

Maximum span between piers	30 m
Maximum deck weight (fresh concrete – 26 kN/m^3)	247 kN/m
Maximum formwork weight	15 kN/m
Maximum wind speed (launching stage)	40 km/h
Minimum plan curvature radius	1000 m
Maximum longitudinal slope	2%
Maximum mid-span deflection during deck concrete pouring stage	2,5 mm

After a period of approximately 16 + 4 + 2 weeks for manufacturing 1), on site assemblage 2) and final tests 3), 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.

This equipment was used for the construction of 23 spans. Energy supply failure situations have occurred without implying any perturbation in the process and no technical problems were recorded. Construction lasted 32 days less than scheduled [6].

3 NEW APPLICATIONS

The application of OPS allows the attainment of 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.

3.1 Overhead movable scaffolding system for single span construction of bridge decks

The first equipment to be presented is an overhead movable scaffolding system (Fig. 4) 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 OPS during concrete the pouring and deck prestressing stages.

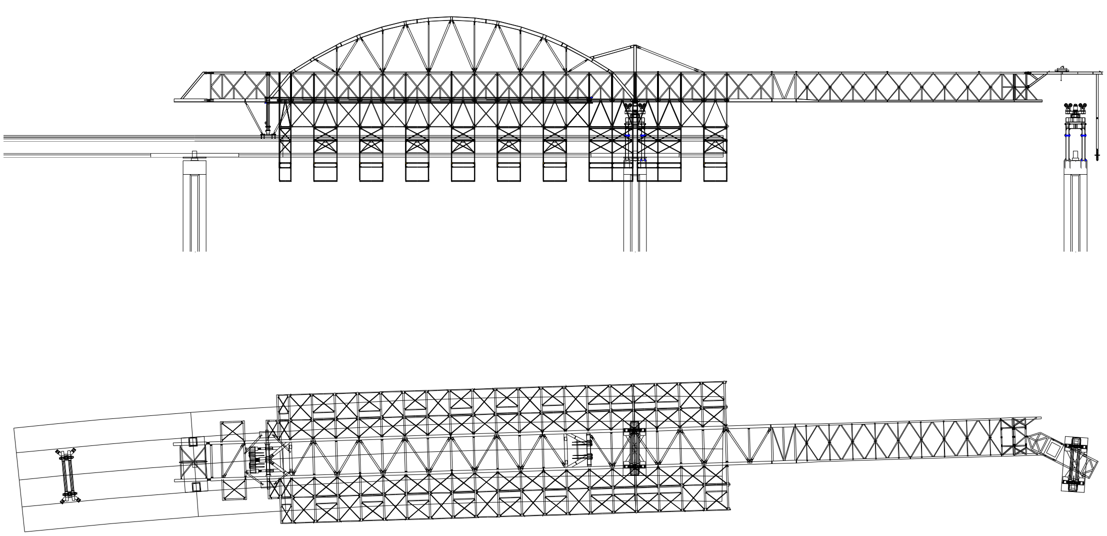

Figure 4: Elevation and plan view of single span construction movable scaffolding system

The superior girder steel structure 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 than 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 the 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 launching feasibility 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 opening capacity (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 on 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.

The OPS system insertion in the main girder is schematically presented in Fig. 5. The main elements are the actuator in the organic anchorage, the unbonded cables, the sensors and the electronic controller in the girder control unit [2,5,7,8].

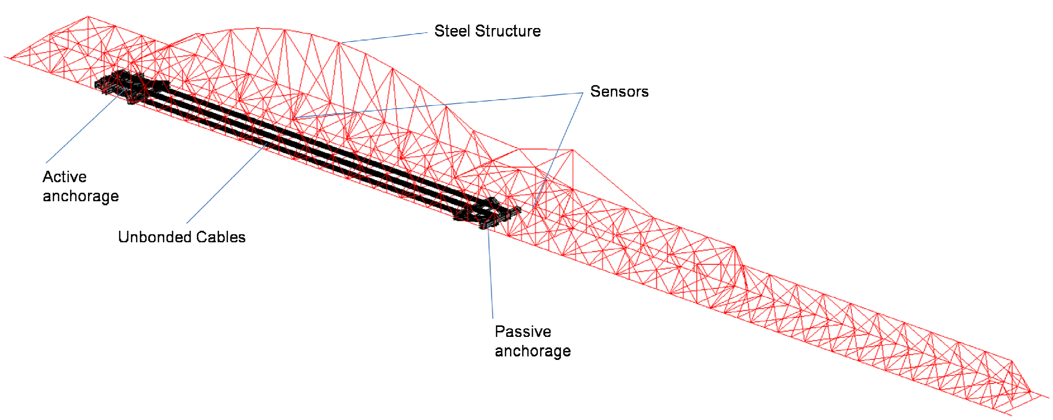

Figure 5: 3D scheme of an overhead movable scaffolding system girder equipped with OPS

The control strategy is similar to the first OPS applications, adopting the mid-span vertical deflection as primordial control variable. The mid-span deflection is measured by means of sensors (pressure transducers) strategically spread along the structure. 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 [4,6]. 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’s (actuator) stroke, moving the anchorage beam and simultaneously tensioning four rectilinear prestressing cables.

In addition, OPS performs continuous monitoring of the main girder steel structure, evaluating the main structural parameters and emitting warnings or alarms in case of anomalous situations (for example loose bolts).

An overhead movable scaffolding system constructs the bridge deck beneath the main girder. Therefore, the transversal structures suspending the formwork (Fig. 6) are 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, 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. The threadbars are conveniently positioned to facilitate the placing of prefabricated deck steel reinforcement.

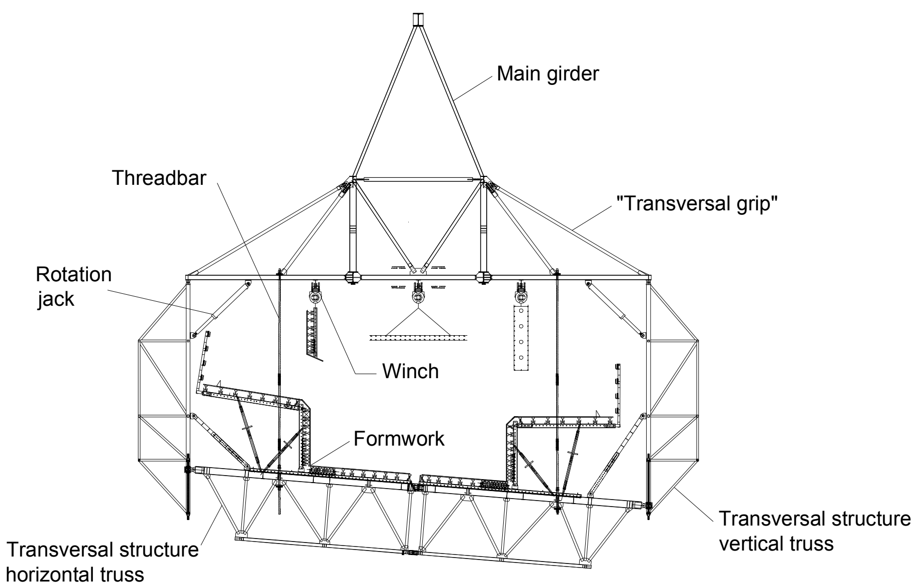

Figure 6: Single span construction movable scaffolding system in concrete pouring position (mid-span cross section)

Before the launching stage, the horizontal trusses are disconnected, the steel threadbars are disassembled and the transversal structures are opened. The opening motion is performed by means of hydraulic jacks actuation, allowing the automatic rotation of transversal structures and formwork.

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 winches for the transportation of pre-fabricated steel reinforcement and prestressing cables ducts directly from the lorry to the construction front, with no need for auxiliary elevation equipment.

3.2 Overhead movable scaffolding system for double span construction of bridge decks

The second equipment to be presented is an overhead movable scaffolding system (Fig. 7) capable of constructing two spans simultaneously per work cycle. This advantage gains relevance as the work extension increases, given that the equipment is able to play the role of two conventional machines without need for duplication of work teams and/or work fronts.

This equipment was specially conceived for construction of 25 m long spans and weights about 270 ton (formwork included). It comprises (a) a modular trussed superior girder with a steel box section of 2,8m x 2,5m and a total length of 83 m weighting 75 ton; (b) transversal structures supporting the formwork, suspended from the main girder in a total extension of 55 m and with a total weight of 50 ton; (c) pier frames, bogies and pier supporting rings making up a total weight of 55 ton and (d) 45 ton of formwork.

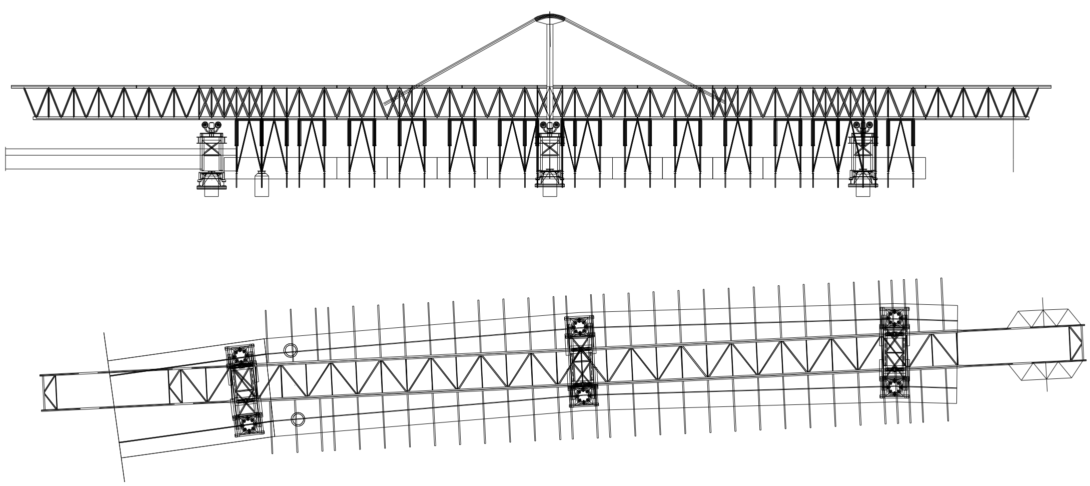

Figure 7: Elevation and plan view of double span construction movable scaffolding system

The double spanned superior girder is equipped with an OPS system materialized by two superior cables deviated at the middle support section by a vertical tower. The cable anchorages (organic anchorage included) are located at the girder mid-span sections. The actuator in the organic anchorage promotes the cables prestressing as the concrete pouring proceeds. In a certain sense, the OPS cables provide the superior girder with two fictitious supports, allowing a 75% reduction of flexural moments (Fig. 8) in the concrete pouring stage. Taking into account the axial forces introduced by the prestressing cables, OPS effect results in a 35% stress reduction, enabling the achievement of a lighter scaffolding structure. As a result, deformations are greatly reduced (up to 85%) and the equipment is provided with a major functional advantage.

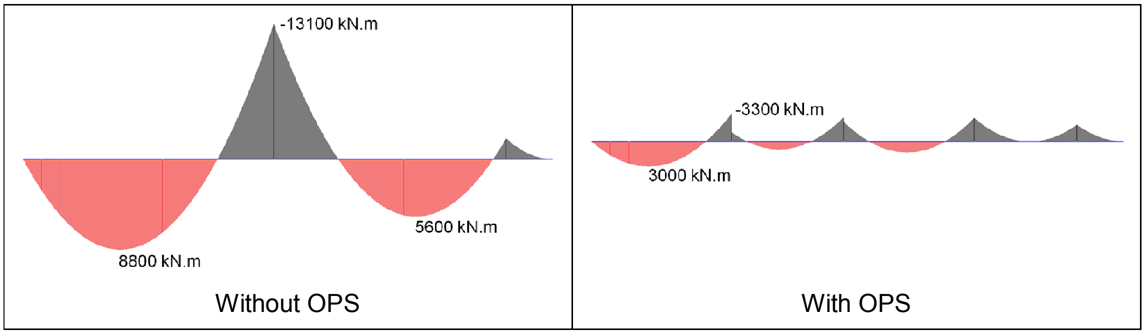

Figure 8: Superior girder flexural moments diagrams in concrete pouring stage

The OPS system strategy is similar to the above described, with a slight difference concerning the control system actuation decision based on the two girder mid-span sections deflection values. This feature requires an increased robustness of the control system warning and alarm routines, related with the response to unexpected deflection values.

The transversal structures opening motion (Fig. 9) is imposed by hydraulic jacks, promoting joint rotation of formwork and transversal structures. The rotation point location allows motion performing in presence of small distances to the ground (minimum free height of 2,2 m).

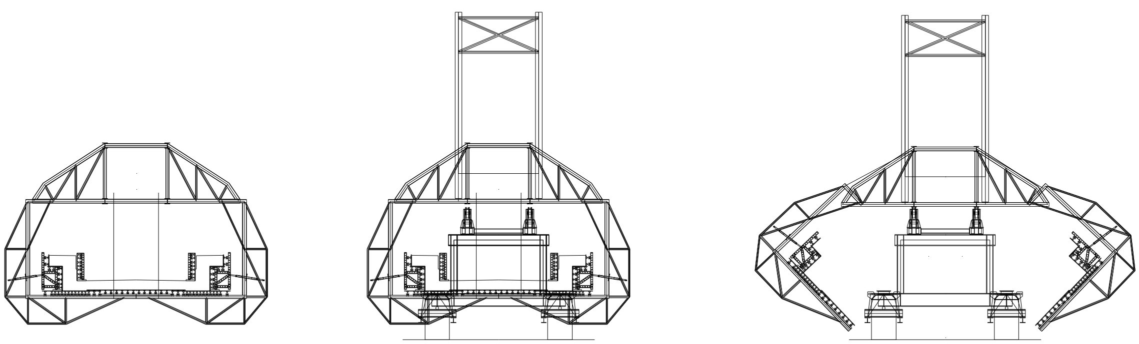

Figure 9: Cross sections of double span construction movable scaffolding system

This movable scaffolding system includes a set of auxiliary equipment which provides practically full autonomy. The disassembling, transportation and assemblage of supporting pier frames, rings and bogies is carried out by its own means, discarding mobile cranes or similar equipment and therefore reducing operational costs making possible the utilization of this equipment in presence of difficult access or inaccessible sites (for example, rivers or swamps). Additionally, the inclusion transportation equipment for the steel deck reinforcement allows its prefabrication on site throughout the concrete curing, contributing to the attainment of demanding construction deadlines.

3.3 Equipment for large span bridge decks construction

In a recent past, it was not reasonable to develop equipments for span by span construction of cast in situ concrete bridges with spans longer than 70 m, because they would be too heavy, robust and extremely difficult to operate and launch. Up until now, the most usual construction process of cast in situ concrete bridges with spans longer than 70 m is the balanced cantilever method, a segmental construction process in which the deck is constructed (by form travellers) through symmetric cantilevers rising from each pier.

However, the OPS technology emergence has brought up a brand new generation of bridge construction equipments, enabling the establishment of new horizons. The third equipment to be presented is a movable scaffolding system (Fig. 10 and Fig. 11) for construction of large span concrete bridges (spans ranging from 70 to 90 m).

Regarding functionality, this hybrid equipment comprises two inferior girders and one superior girder, combining overhead equipment advantages (ability to transport prefabricated deck steel reinforcement and easier longitudinal launching) with underslung equipments simplicity (easy handling and formwork opening operation).

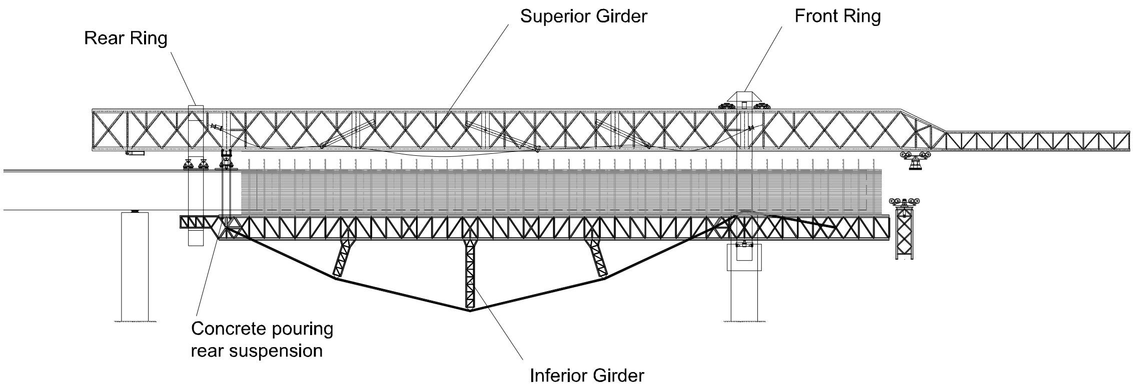

Figure 10: Elevation view of large span construction movable scaffolding system

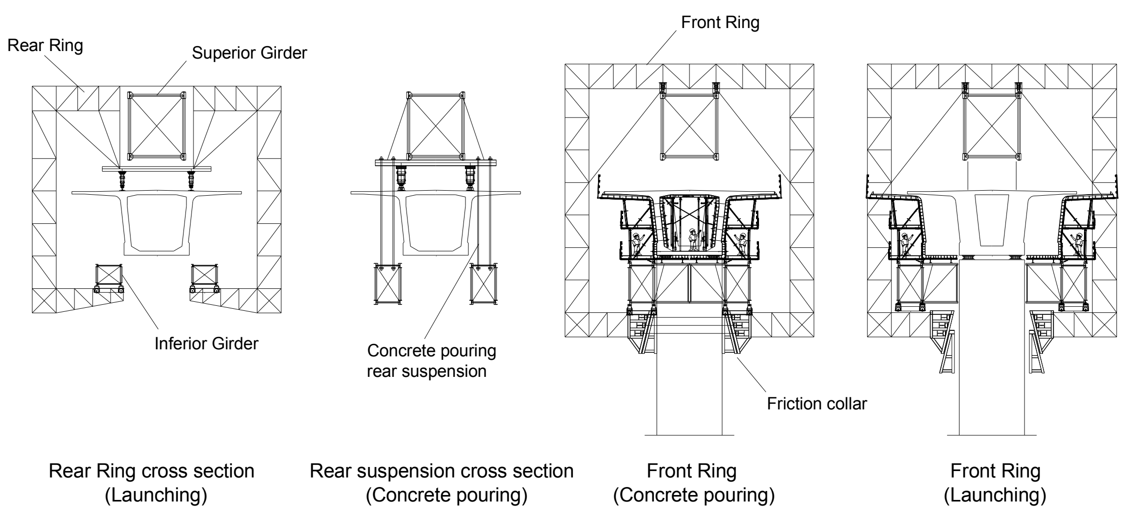

Figure 11: Cross sections of large span construction movable scaffolding system

The two inferior girders are pure scaffold structures, supporting the formwork and the fluid concrete weight, throughout concrete pouring. During this stage, they are supported by a rear suspension from the previously constructed deck and by friction collars located at the front pier (Fig. 11). Since they are not self-launched, their design is fully conditioned by the concrete pouring stage, enabling the achievement of an optimized length (118 m long), cross section (2,00m x 3,00m) and organic prestressing cables layout. The structure slenderness allows a full exploitation of OPS potentialities (Fig. 12), resulting in expressive reductions in maximum flexural moment (75%), stress (60%) and mid-span deflection (98%). Each inferior girder weights about 120 ton.

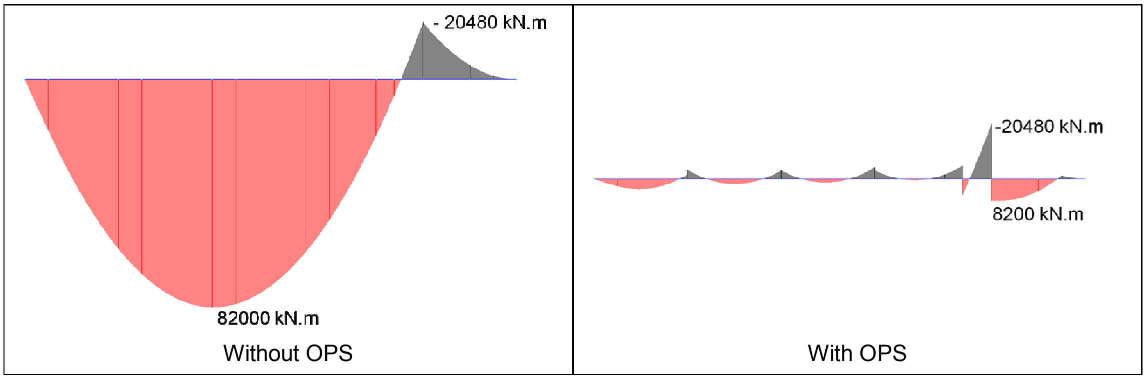

Figure 12: Inferior girder flexural moments diagrams in concrete pouring stage

On the other hand, the superior girder, with a total length of 150 m, is responsible for the movable scaffolding system launching (Fig.13). In a first stage, the superior girder is self-launched towards a supporting frame located at the next pier.

Then, the entire inferior set (inferior girders and formwork) is supported by two movable elements (rings). The Rear Ring backs up the rear part of the inferior girders and is launched over a rail located above the previously constructed deck. The Front Ring incorporates the supporting friction collars and is equipped with a set of steel wheels that allows it to move over the superior chord of the superior girder, promoting the launching of the entire inferior set. During this stage, the Front Ring transmits a concentrated load of 450 ton to the OPS equipped superior girder. The OPS system (similar to the above mentioned) improves the superior girder structural behaviour in a most significant manner (68% flexural moment reduction, 50% stress reduction and 94% deformation reduction), making viable a 4,50m x5,00m cross section and a total weight of 270 ton.

In global terms this equipment weights about 950 ton, being easier to handle and safer than the conventional equipments, since great part of the travelling weight (rings, formwork and inferior girders) is launched through a perfectly fixed "railway".

In comparison with balanced cantilever construction equipments, the following advantages are identified:

- Significant reduction of construction time (construction of 1 span per cycle);
- Deck prestressing cost reduction (30%):
    - Reduction of deck prestressing amount (no cantilever moments);
    - Reduction of the number of anchorages and couplers;
    - Reduction of number of prestressing operations in the deck;
- Reduction of the number of high risk operations (movements and launchings);
- Easier deck geometry control;
- Inexistence of cantilever disequilibrium problems during the deck construction (discarding of deck stabilizing ties);
- Total autonomy – doesn't need auxiliary means to install the front pier frame and to transport workers and equipment to the work front.

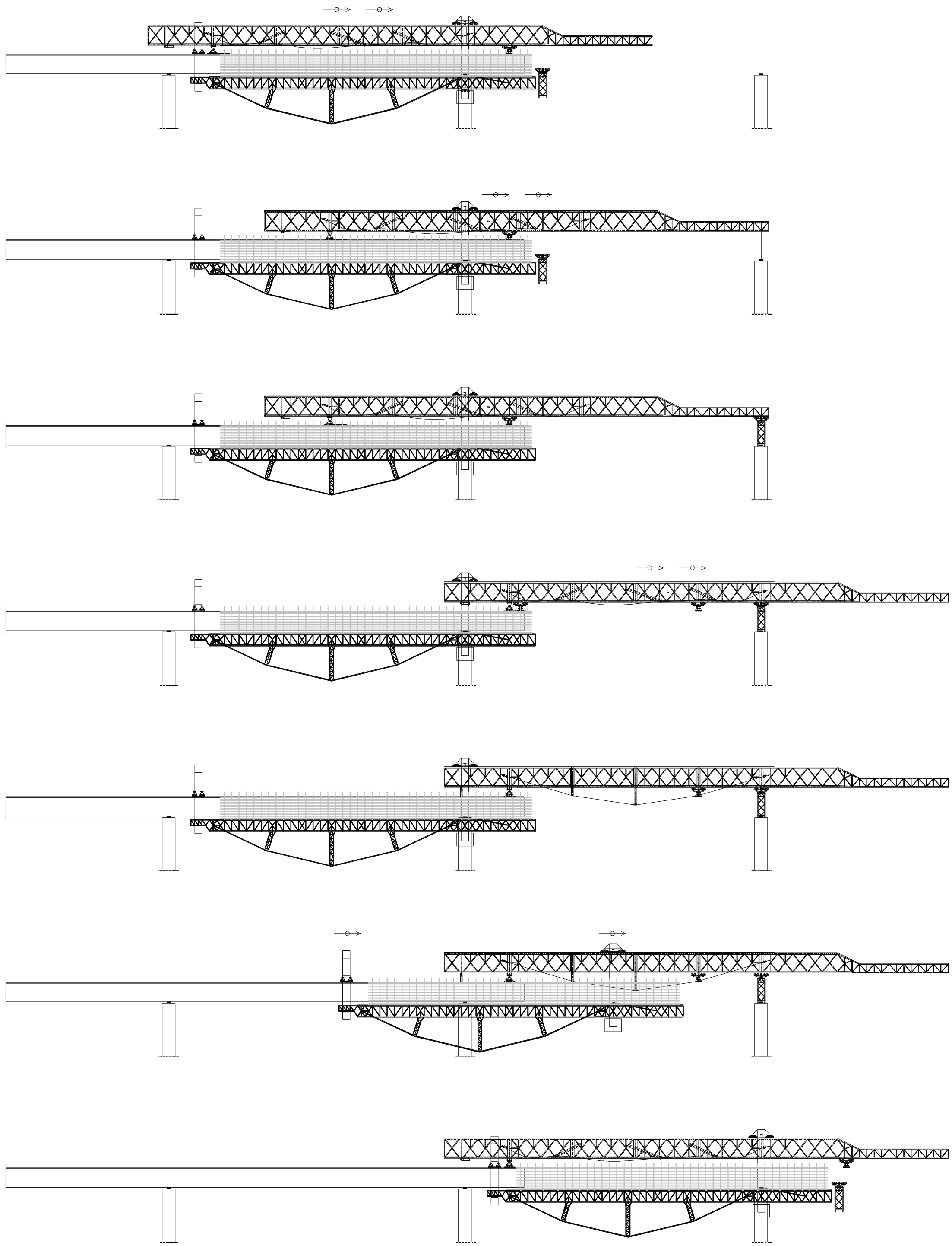

Figure 13: Launching of large span construction movable scaffolding system

4 CONCLUSIONS

The first full scale application of a movable scaffolding system strengthened with OPS confirmed that OPS is simple and feasible. Rio Sousa was merely the first of a new generation of structures. The conjugation of OPS technology with different types of structural systems gave rise to highly efficient steel structures, allowing the achievement of extremely light and functional movable scaffolding systems. The following advantages standout, in comparison with current equipments:

- Higher load capacity;
- Reduction of the equipment weight;
- Reduction of the acquisition costs;
- Reduction of operational costs;
- Mid-span deflection control and ability to program deflections;
- Continuous monitoring of the scaffolding structure, enabling higher safety levels;
- Simplicity of steel connections (maximum tensions substantially reduced);
- Ability to construct cast in situ concrete bridge decks with spans ranging from 70 m to 90 m.

Moreover, implementation of OPS technology in movable scaffolding systems 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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REFERENCES

[1] P. Pacheco and António Adão da Fonseca, “Effector Systems in Structures”, Conceptual design of structures – Proceedings of IASS Symposium, Stuttgart, 339-346 (1996).

[2] P. Pacheco and António Adão da Fonseca, “Organic Prestressing – an Effector System example (in Portuguese)”, PhD Thesis, Dep. Civil Eng., Faculty of Engineering of University of Porto, (1999).

[3] P. Pacheco, “Organic Prestressing – an example of an Effector System”, *Structural Concrete Journal of the Fib*, 3, 107-113, (2002).

[4] P. Pacheco and António Adão da Fonseca, “Organic Prestressing”, *Journal of Structural Engineering*, ASCE, March 2002, 400-405.

[5] A. André. P. Pacheco and António Adão da Fonseca, “Experimental study of a launching gantry reduced scale model strengthened with organic prestressing”, *Structural Engineering International, Journal of the IABSE*, 16, 49-52, (2006).

[6] P. Pacheco, A. Guerra, P. Borges and H. Coelho, “A Scaffolding System strengthened with Organic Prestressing – the first of a new Generation of Structures”, *Structural Engineering International, Journal of the IABSE*, 17, 314-321, (2007).

[7] A. André, “Experimental study of a launching gantry reduced scale model strengthened with organic prestressing (in Portuguese)”, MSc Thesis, Dep. Civil Eng., Faculty of Engineering of University of Porto, (2005).

[8] P. Pacheco et al, “Strengthening by organic prestressing of existing launching gantries in the construction of high speed railway bridge decks”, Workshop Bridges for High Speed Railways, Porto, 289-299, (2004).