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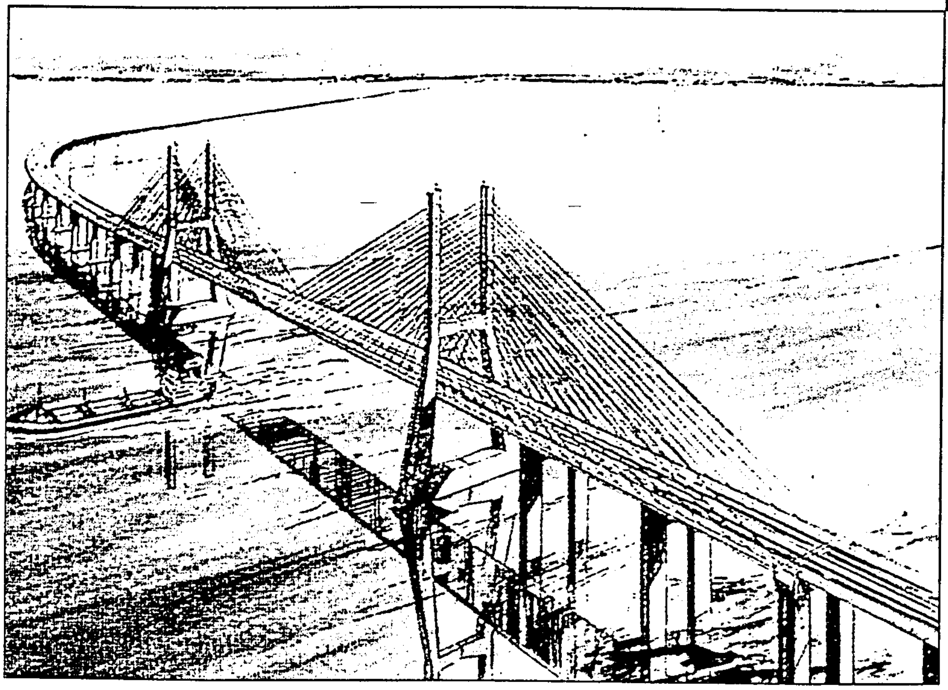

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S. Pompeu Santos • António M. Baptista

ORGANICALLY PRESTRESSED MULTI-SPAN CONTINUOUS BOX GIRDERS

Pedro A. R. PACHECO
Civil Engineer, MSc
PhD Student
University of Oporto, Portugal

António ADÃO DA FONSECA
Civil Engineer, PhD, DIC
Professor of Bridge Design
University of Oporto, Portugal

SUMMARY

A brief reference to organic prestressing research is presented and the most relevant concepts are expressed together with the corresponding control algorithms. An example is used to emphasize the performarnce of organic structural solutions.

1. INTRODUCTION

New concepts of structural control have been proposed recently under names of "parastressing" [1] and of "effector systems" [2]. Both involve control systems where actuators are not external suplementary elements, rather are structural elements themselves. An useful example of effector system is provided by organic prestressing systems (OPS), which have been object of several numerical analysis [2,3]. The execution of a prototype is envisaged but its reliability offers no doubt, because OPS make use of well known technologies.

OPS allow for an "optimized" prestressing, because permanent undesirable stresses are avoided and prestresssing time-dependent losses are greatly reduced. Furthermore, OPS permit the design of lighter and more slender structures for the same structural materials. These structural solutions do fit particularly well to situations of high "live-load/dead-load" ratio.

Fundamental concepts and basic mathematical expressions for the algorithms of an efficient control strategy are presented briefly in the following. By means of an example, the performance of structures with OPS is studied through some relevant design parameters.

2. METHODOLOGY AND FORMULATION

A very simple methodology was first developed for simply supported beams [3]. An effective control system with no controller was achieved, where the main objective was to ensure no tensions (or even low compressions) could be generated at predefined control sections. The corresponding algorithm consists on a sequence of two steps. If low compression or high compression are to be avoided, a "signal" is sent by sensors (step one) if one of those limiting values is reached and, respectively, a "contraction" or "release" (previous contraction is canceled) process takes place (step two). In mathematical terms, this is stated by expressions (1):

$$\begin{cases} \Delta_{ai} < \sigma_{Sci}(G) + \sigma'_{Sci}(Q) + nc_t \times \overline{\sigma}^i_{Sci} < \Delta_{ci} & \Rightarrow \quad nc_{t+\Delta t} = nc_t \\ \sigma_{Sci}(G) + \sigma'_{Sci}(Q) + nc_t \times \overline{\sigma}^i_{Sci} > \Delta_{ci} & \Rightarrow \quad nc_{t+\Delta t} = nc_t + 1 \\ \sigma_{Sci}(G) + \sigma'_{Sci}(Q) + nc_t \times \overline{\sigma}^i_{Sci} < \Delta_{ai} & \Rightarrow \quad nc_{t+\Delta t} = nc_t - 1 \end{cases} \tag{1}$$

where σ_{Sci} (G) is the stress on the control section *i* due to dead loading;
σ'_{Sci} (Q) is the stress on the control section *i* due to live loading at the instant t;
$\overline{\sigma}^i_{Sci}$ is the stress amplitude produced by one contraction;
$nc_t \cdot \overline{\sigma}^i_{Sci}$ is the stress on the control section *i* due to action of the organic prestressing at instant *t*;
Δ_{ci} and Δ_{ai} are the compression margin and the activity margin of the organic system; (these are the stress levels that make the sensors produce signals); and
nc_t and $nc_{t+\Delta t}$ are the number of active contractions at instants t and t+Δt.

Expressions (1) together with expressions (2) define the activity law of a single OPS system.

$$\begin{cases} nc_t = 0 & \Rightarrow \quad \Delta_{ai} = -\infty \\ nc_t = nc_{max} & \Rightarrow \quad \Delta_{ci} = +\infty \end{cases} \tag{2}$$

The generalisation of this algorithm to continuous beams is established in a similar manner if the problem is considered by taking each single span at a time.

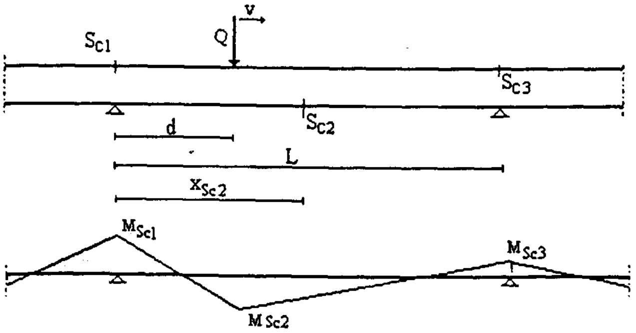

Figure 1: General span of a continuous beam with a moving concentrated load.

For example, for the general span represented in figure 1, three control sections S_{c1}, S_{c2} and S_{c3} are taken and respective stress histories at relevant fibres are shown in figure 2.

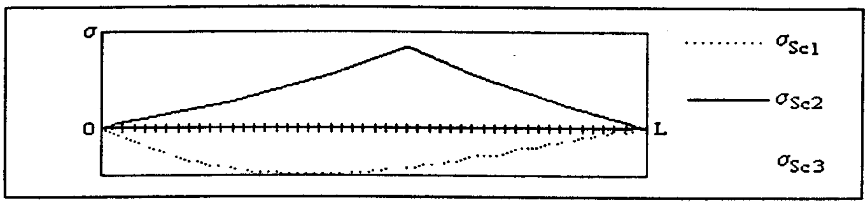

Figure 2: Stress evolution at relevant fibres of control sections due to action of moving load

The stress values at relevant fibres of any control section of the span can be controlled by the action of two cables in the span, as shown in figure 3. For an extreme span, one single cable is sufficient.

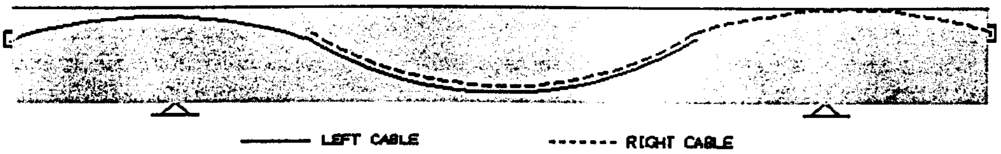

Figure 3: Solution of two cables per span for stress control in a general span

Therefore, the stress control of continuous beams with n spans is achieved by means of n_{oc} (=2n-2) prestressing cables. The corresponding activity law is expressed by sets of expressions (1), with each cable now subordinated to two control sections. This implies an activity law for cable jth as stated in expressions (3).

$$\begin{cases} \sigma_{Sc1j} > \Delta_{c1j} \wedge \sigma_{Sc2j} > \Delta_{c2j} & \Rightarrow ncj_{t+\Delta t} = ncj_t + 1 \\ \sigma_{Sc1j} < \Delta_{a1j} \vee \sigma_{Sc2j} < \Delta_{a2j} & \Rightarrow ncj_{t+\Delta t} = ncj_t - 1 \\ (\sigma_{Sc1j} > \Delta_{a1j} \wedge \sigma_{Sc2j} > \Delta_{a2j}) \wedge (\sigma_{Sc1j} < \Delta_{c1j} \vee \sigma_{Sc2j} < \Delta_{c2j}) & \Rightarrow ncj_{t+\Delta t} = ncj_t \end{cases} \tag{3}$$

where

$$\sigma_{Sci_j} = \sigma_{Sci_j}(G) + \sigma^t_{Sci_j}(Q) + \sum_{j=1}^{2} nc_{jt} \cdot \overline{\sigma}^i_{Sci_j} \tag{4}$$

Expression (4) implies that the stress level depends upon the loading history, because it affects the number of contractions at instant *t*. Notwithstanding, if the loading history $Q_k(t)$ is known, the general case of a continuous beam with n spans and n_{oc} organic cables can be considered by general expression (5), leading to an activity matrix M_{ac} for each loading history that relates instant *t* with the activity state of the organic cables.

$$\sigma_{Sci_j} = \sigma_{Sci_j}(G) + \sigma_{Sci_j}(Q_k) + \sum_{j=1}^{n_{oc}} nc_{jk} \cdot \overline{\sigma}^i_{Sci_j} \tag{5}$$

Column k of the matrix relates to a loading phase k of a specific loading history and defines the number of contractions of every cable.

$$M_{ac}^{Q^k} = \begin{bmatrix} nc_1^{\,1} & nc_1^{\,2}\ldots\ldots & nc_1^{\,k}\ldots\ldots & nc_1^{\,nk} \\ nc_2^{\,1} & nc_2^{\,2}\ldots\ldots & nc_2^{\,k}\ldots\ldots & nc_2^{\,nk} \\ nc_3^{\,1} & nc_3^{\,2}\ldots\ldots & nc_3^{\,k}\ldots\ldots & nc_3^{\,nk} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ nc_j^{\,1} & nc_j^{\,2}\ldots\ldots & nc_j^{\,k}\ldots\ldots & nc_j^{\,nk} \\ \cdots\cdots & \cdots\cdots & \cdots\cdots & \cdots\cdots \\ nc_{noc}^{\,1} & nc_{noc}^{\,2}\ldots\ldots & nc_{noc}^{\,k}\ldots\ldots & nc_{noc}^{\,nk} \end{bmatrix} \qquad (6)$$

The complete definition of the organic structural behaviour is established by all activity matrices, one for every loading history. It should be noted that the interactivity of cables is automatically accounted for.

3. NUMERICAL EXAMPLE

This example is chosen to exhibit the OPS potentialities and is taken from a real problem. The project consisted of two parallel viaducts flying over a road junction and located on top of an underground metro station (see figure 4). Free height requirements and need for the lightest structure, together with cost of alternative in steel, meant a prestressed concrete box girder solution was chosen. This design was optimised with a 1.50 m constant depth box girder and a global conventional longitudinal prestressing force of 6 015 750 kN.m.

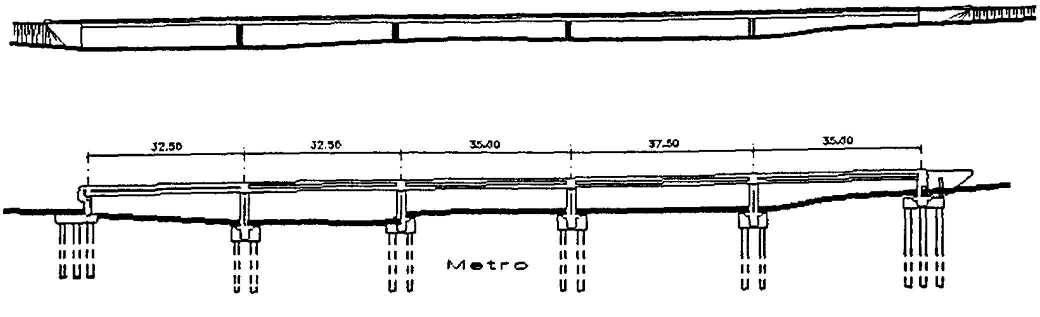

Figure 4: Elevation and longitudinal section of the viaducts

The alternative non-conventional, that is, organic, prestressing design accounts for identical loads and design criteria, both taken from several texts and codes of practice [4,5,6,7,8,9]. A lighter box girder of 1.35m constant depth was designed with a global longitudinal prestressing force of 6 025 880 kN.m (0.2% more than conventional prestressing). 27 % of that total was taken by OPS.

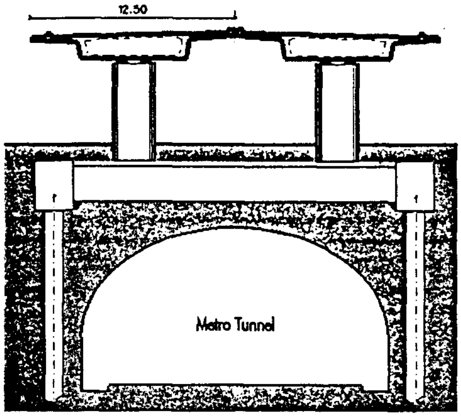

Figure 5: Cross section of viaducts

Figures 6 and 7 represent the stress history and contractions of all organic cables for a specific distributed loading case and for a concentrated load of 625 kN moving from left to right at a speed of 50 km/h. Obviously, delay in response of the OPS explains the higher number of contractions of the right cable.

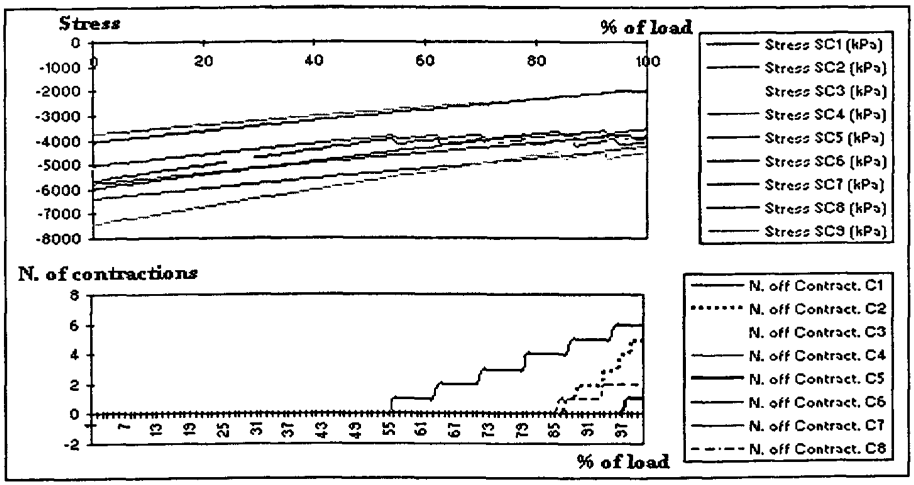

Figure 6: Stress evolutions and organic cables contactions with a destributed continuous loading on three spans.

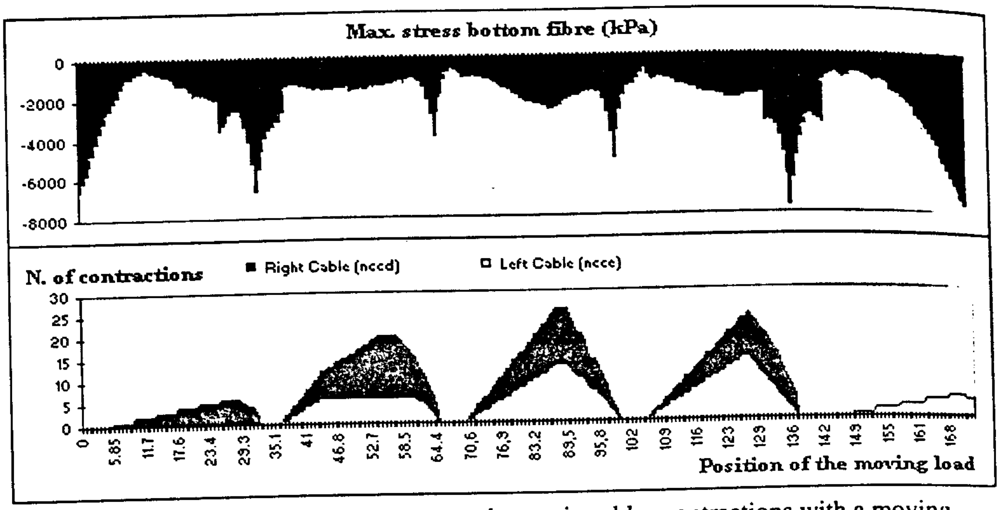

Figure 7: Maximum bottom stresses and organic cables contractions with a moving concentrated load.

The OPS solution leads to better stress distributions, as shown in figure 9, but the following parameters have to addressed most carefully:

- fatigue damage in organic cables,
- deformations, and
- vibrations.

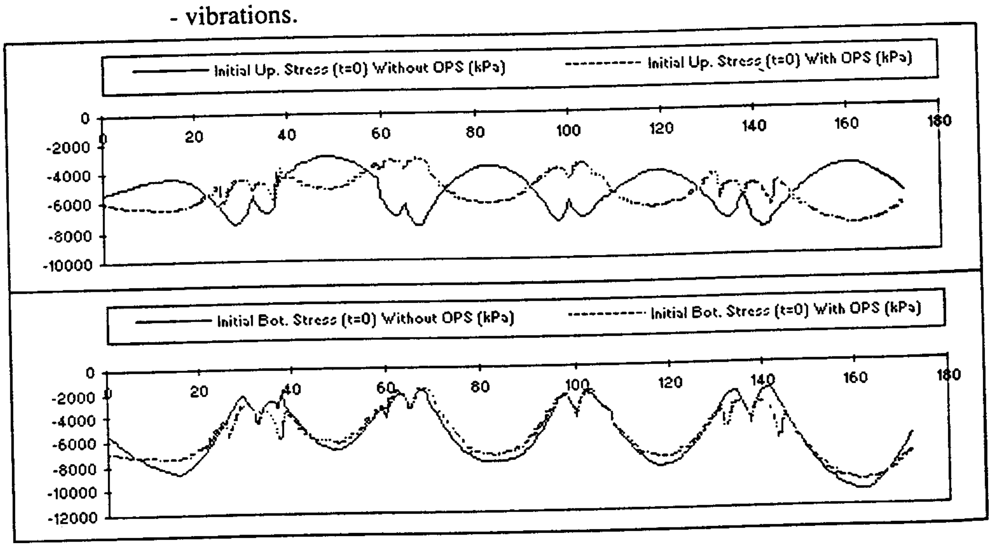

Figure 8: Initial stresses at upper and bottom fibres with and without OPS

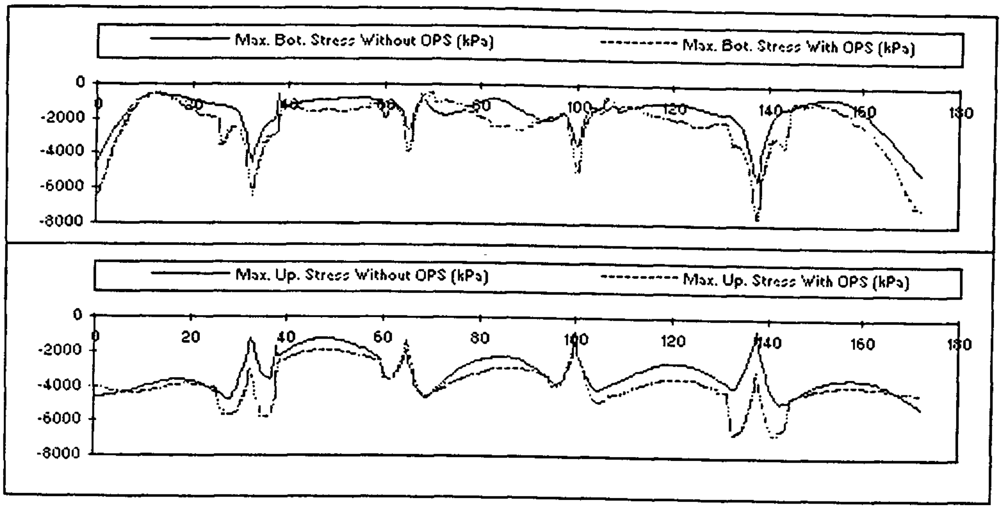

Figure 9: Service maximum stresses at the bottom and upper fibres with and without OPS

The maximum deflection for the OPS solution (15 mm) is bigger than for the conventional one (13mm), but they are both acceptable (Δ = L/2558 and Δ = L/2856, respectively). The same happens with vibrations. According to Rausch method, the conventional solution falls within Class A and the OPS one falls within Class B (Classes A,B,C and D are acceptable) [7]. Fatigue control is performed by a comulative calculation of damage according to Palmgreen-Miner's rule. This damage results from the stress variations on the organic cables that are generated when contraction/release cycles take place. Figure 10 shows that organic cables 2 and 7 require replacement after 20 years of service.

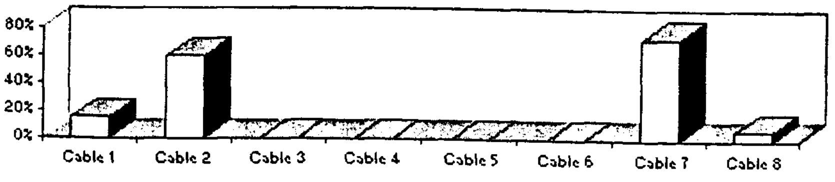

Figure 10: Fatigue damage on the organic cables after 20 years

4. CONCLUSIONS

OPS's solutions can be designed with simple and efficient control strategies. Deformations, vibrations and fatigue damage have to be controlled most carefully but should not imply major difficulties. The great reduction of prestressing losses and the organic control allows for a more rational use of prestressing. OPS solutions may be a consistent and effective alternative to conventional prestressing solutions, specially when lightness and slenderness are desired.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Montens, S. - "A Global Concept for 21st Century Bridges: Parastressing" in *FIP Symposium on Post-Tensioned Concrete Structures*, London, 1996, p. 739-746

[2] Pacheco, P.; Adão da Fonseca, A. - "*Effector Systems in Structures*" - in *Conceptual Design of Structures* - Proceddings of IASS Symposium, Stutgard, 1996, p. 339-346

[3] Pacheco, P.; Adão da Fonseca A. - "Organic Structures Design" (in Portuguese), in *Betão Estrutural 96* - Proceddings of GPPE Symposium, Lisboa, 1996, p. 1.97-1.108

[4] ACI - Part-4 (Manual of Concrete Practice), "Bridge Analisys and Design", (5.7.6. - Fatigue), 1993, pp 343R-67

[5] Eurocode 2, ENV 1992 "Design of Concrete Structures Part 2 - Concrete Bridges", Draft 8, 1994, p. 5-15

[6] FIP - *Recommendations for the Design of Post-Tensioned Slabs and Foundation Rafts* (1995), Waiting for Publication, p. 11-20

[7] Menn, C. - *Prestressed Concrete Bridges*. Birkhauser Verlag, 1986, p. 192-197

[8] Ontario Ministry of Transportation and Communications, "*Ontário Highway Bridge Design Code and Commentary*", 1983

[9] Regulamento Estruturas Betão Armado e Pré-esforçado, Porto Editora, 1993, p. 52-60