Organic Prestressing

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Abstract: The concept of prestressing of civil engineering structures is well known, consisting of the introduction of a set of self-equilibrating forces upon the structure that will try to counteract the internal forces generated in the structure by the external actions. Those prestressing forces depend upon the layout and forces of the cables, not accounting for the variations on the external actions during the life of the structure. The rapid technological evolution of the last quarter of the 20th Century gave credit to structural solutions with adaptive behavior–*intelligent structures*. Organic prestressing is part of that environment. But it is no more than a prestressing system under *on-line* control, capable of variation in the forces introduced in the cables, thus improving significantly the prestressing effect. A brief reference to organic prestressing research is presented and the most relevant concepts are described together with the corresponding control algorithms. Undesirable control phenomena are defined and measures to avoid them are presented. Main technological aspects are mentioned. An example is used to emphasize the performance of organic structural solutions.

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Introduction

New concepts on active structural control have been proposed at the end of last decade under the names of ''parastressing'' (Montens 1996) and of ''effector systems'' (Pacheco et al. 1996). Both involve control systems where actuators are not external supplementary elements, but rather are structural elements themselves. A useful example of an effector system is provided by organic prestressing systems (OPS) which have been object of several numerical applications (Pacheco et al. 1996; 1997a,b; Pacheco 1999)]. A prototype is under execution, but its resilience offers no doubt, since OPS makes use of well-known technologies.

OPS allows for an ''optimized'' prestressing, because permanent undesirable stresses are avoided and prestressing time-dependent losses are greatly reduced. Furthermore, OPS permit the design of lighter and more slender structures with 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. Undesirable control phenomena are defined and simple rules to avoid them are proposed. Essentials of OPS technology are synthetically mentioned. By means of one example, the performances of structures with OPS are synthetically presented through some relevant design parameters.

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Methodology and Formulation

A very simple methodology was first developed for simply supported beams (Pacheco et al. 1996a). An effective control system was achieved, where the main objective was to ensure no tensions (or even low compressions) could be generated at predefined control cross sections. The corresponding algorithm consists of a sequence of two steps. If low compression or high compression are to be avoided, a ''signal'' is sent by sensors (step one) when 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 expression (1):

$$\begin{aligned}
&\Delta_{ai}<\sigma_{\mathrm{Sci}}(G)+\sigma^{t}_{\mathrm{Sci}}(Q)+nc_t\times\bar{\sigma}^{\mathrm{OPS}}_{\mathrm{Sci}}<\Delta_{ci}\Rightarrow nc_{t+\Delta t}=nc_t\\
&\sigma_{\mathrm{Sci}}(G)+\sigma^{t}_{\mathrm{Sci}}(Q)+nc_t\times\bar{\sigma}^{\mathrm{OPS}}_{\mathrm{SCi}}>\Delta_{ci}\Rightarrow nc_{t+\Delta t}=nc_t+1\\
&\sigma_{\mathrm{Sci}}(G)+\sigma^{t}_{\mathrm{SCi}}(Q)+nc_t\times\bar{\sigma}^{\mathrm{OPS}}_{\mathrm{Sci}}<\Delta_{ai}\Rightarrow nc_{t+\Delta t}=nc_t-1
\end{aligned}\tag{1}$$

where $\sigma_{\mathrm{Sci}}(G)$ = the stress at the relevant fiber in control cross section i due to dead loading; $\sigma^{t}_{\mathrm{Sci}}(Q)$ = the stress at the relevant fiber in control cross section i due to live loading at instant t; $\bar{\sigma}^{\mathrm{OPS}}_{\mathrm{Sci}}$ = the stress increment at the relevant fiber in control cross section i produced by one contraction; nc_t and $nc_{t+\Delta t}$ = the number of active contractions at instants t and $t+\Delta t$; $nc_t\times\bar{\sigma}^{\mathrm{OPS}}_{\mathrm{Sci}}$ = the stress at the relevant fiber in control cross section i due to action of the organic prestressing at instant t; Δ_{ci} and Δ_{ai} = the compression margin and the activity margin of the organic system (these are the stress levels that make the sensors produce signals).

Eq. (1) and the following equation, together, define the following activity law of a single OPS system:

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

where $nc_{\max}$ = maximum number of contractions that the system is able to execute.

The generalization of this algorithm to continuous beams is established in a similar manner if the problem takes each single span at a time. For example, for the span represented in Fig. 1,

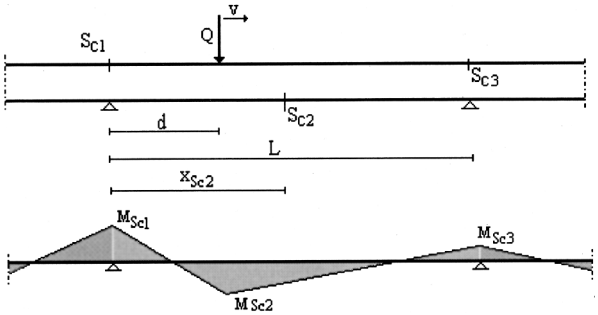

Fig. 1. Flexural moments at current span of continuous beam under one moving concentrated load

three control cross sections S_{c1}, S_{c2}, and S_{c3} are considered and the corresponding stress histories at relevant fibers are shown in Fig. 2. Those stresses can be controlled by the action of two prestressing cables in the span, as shown in Fig. 3, where the left cable is subordinated to control sections S_{c1} and S_{c2} and the right cable is subordinated to control sections S_{c2} and S_{c3}. For an extreme span, one single cable is sufficient.

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

$$\begin{aligned}
&\sigma^t_{Sc1_j}>\Delta_{c1_j}\wedge\sigma^t_{Sc2_j}>\Delta_{c2_j}\Rightarrow nc^j_{t+\Delta t}=nc^j_t+1\\
&\sigma^t_{Sc1_j}<\Delta_{a1_j}\vee\sigma^t_{Sc2_j}<\delta_{a2_j}\Rightarrow nc^j_{t+\Delta t}=nc^j_t-1\\
&(\sigma^t_{Sc1}>\Delta_{a1_j}\wedge\sigma^t_{Sc2_j}>\Delta_{a2_j})\wedge(\sigma^t_{Sc1_j}<\Delta_{c1_j}\vee\sigma^t_{Sc2_j}<\Delta_{c2_j})\\
&\qquad\Rightarrow nc^j_{t+\Delta t}=nc^j_t
\end{aligned}\tag{3}$$

where

$$\sigma^t_{\mathrm{Sci}_j}=\sigma_{\mathrm{Sci}_j}(G)+\sigma^t_{\mathrm{Sci}_j}(Q)+\sum_{j^*=1}^{2}[nc^{j^*}_t\times\overline{\sigma}^{j^*}_{\mathrm{Sci}_j}]\tag{4}$$

Eq. (4) implies that the stress level depends upon the loading history, because it affects the number of contractions at instant t (*corresponding to loading phase k*). Notwithstanding, if the loading history $Q_h(t)$ [or $Q_h(k)$] is known, the general case of a continuous beam with n spans and n_{oc} organic cables can be considered by the following general expression:

$$\sigma^k_{\mathrm{Sci}_j}=\sigma_{\mathrm{Sci}_j}(G)+\sigma^k_{\mathrm{Sci}_j}(Q_h)+\sum_{j^*=1}^{n_{oc}}[nc^{j^*}_k\times\overline{\sigma}^{*}_{\mathrm{Sci}_j}]\tag{5}$$

leading to an activity matrix M_{ac} for each loading history that relates instant t with the activity state of the organic cables. Column k of the matrix relates to a loading phase k of a specific loading history $Q_h(k)$ and defines the number of contractions of every cable.

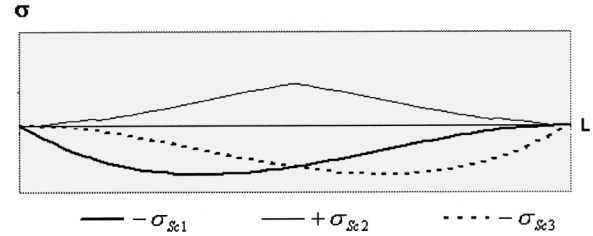

Fig. 2. Stress evolution at relevant fibers of control cross sections due to action of moving load

$$M^{Qb}_{ac}=\begin{bmatrix} nc^1_1 & nc^1_2 & nc^1_k & nc^1_{nk}\\ nc^2_1 & nc^2_2 & nc^2_k & nc^2_{nk}\\ nc^3_1 & nc^3_2 & nc^3_k & nc^3_{nk}\\ nc^j_1 & nc^j_2 & nc^j_k & nc^j_{nk}\\ nc^{n_{oc}}_1 & nc^{n_{oc}}_2 & nc^{n_{oc}}_k & nc^{n_{oc}}_{nk}\end{bmatrix}\tag{6}$$

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

The delay of the response (both mechanical and electronic), as well as the consideration of any loading configuration, can be easily integrated into this methodology with no change in the fundamental logic procedures implicit in the mathematical expressions. This is explained in detail in (Pacheco 1999).

Solutions to Avoid Control Undesirable Phenomena

Two main phenomena may occur when this control strategy is applied: instability and hyperactivity.

Instability occurs when a process of activity cycles, with alternate positive and negative signals, starts (see Fig. 4). This may happen if the stress $\overline{\sigma}^{\mathrm{OPS}}_{\mathrm{Sc}}$ control increment is high when compared with the modulus of control margins difference ($|\Delta_a-\Delta_c|$).

For example, when there is only one control system, instability is avoided if the algorithm verifies condition (7):

$$|\overline{\sigma}^{\mathrm{OPS}}_{\mathrm{Si}}|<|\Delta_a-\Delta_c|-\sum|\delta i|\tag{7}$$

where $\Sigma|\delta_i|$ represents the sum of the uncertainties modulus. Similar expressions are known to account for multisystem instability problems (Pacheco 1999). If dynamic effects are important, the correspondent criteria ought to be introduced (Pacheco 1999).

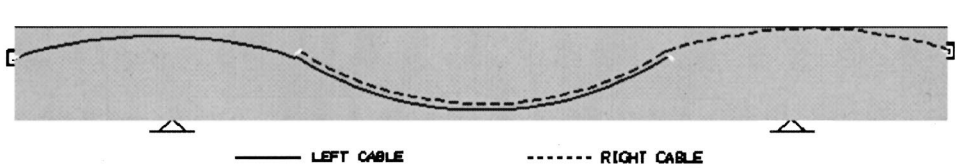

Fig. 3. Solution of two prestressing cables per span for stress control in current span

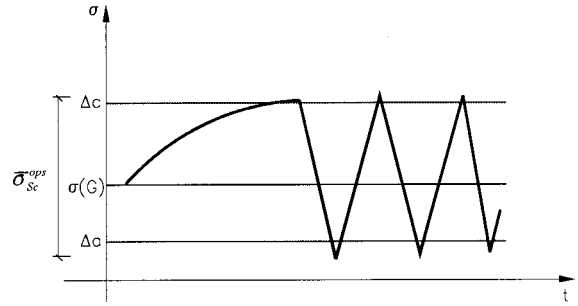

Fig. 4. Instability

Hyperactivity occurs when a process of activity cycles, with identical signals on each control system, starts. The prestressing hyperstatic effect associated with an OPS activity at instant k can lead to hyperactivity by inducing the activity of other cables at instant $k+1$, which in term may induce more activity on the first, and so on (see Fig. 5).

Hyperactivity is mathematically controlled with some well-known algebra techniques. Indeed, stress evolution on the control fibers due to the control action can be expressed in a modal formulation (Pacheco 1999).

$$[\overline{V}_{TT}]_i = \sum_{I=1}^{n_{oc}} \phi_I \cdot \sigma_I^* \cdot [V_a^I]_i \tag{8}$$

where I = an interactivity mode; ϕ_I = the modal contribution factor; σ_I^* = the stress increment for contraction in I interactivity mode; $[V_a^I]_i$ = the activity vector in I interactivity mode; $[\overline{V}_{TT}]_i$ = the vector of stress increments.

Obviously, for each interactivity mode I, it is possible to evaluate the following stress increment produced by contraction of all OPS systems at jth control basis (which includes the two control fibers that activate jth OPS system):

$$\sigma_{I,j}^{\mathrm{INT}} = \sigma_I^* \cdot [V_a^I]_{i=j} \tag{9}$$

The interactivity coefficient

$$C_j^I = -\frac{\sigma_{I,j}^{\mathrm{INT}}}{\sigma_j^{\mathrm{OPS}_j}} \tag{10}$$

is then the ratio between the control stress produced at control basis j by all OPS systems in an interactivity mode and the same stress produced by one OPS system on the respective two control cross sections $\sigma_j^{\mathrm{OPS}_j}$. If the stress produced by "other" control systems in control basis j is as high as the stress produced by OPS system j, then hyperactivity could occur. This is overcome by imposing condition $C_j^I \leq 1$ for all OPS systems and on all interactivity modes.

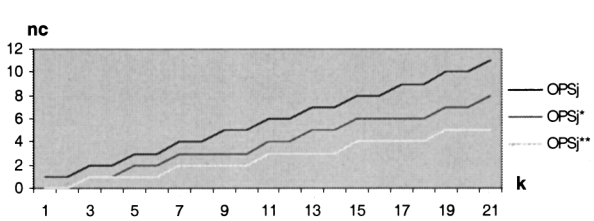

Fig. 5. Hyperactivity occurring on three OPS systems

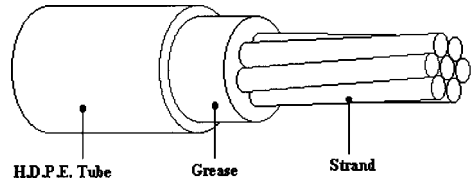

Fig. 6. Unbounded tendon

In common structures, hyperactive problems are not to be expected because the prestressing hyperstatic effect is not supposed to be very high.

It should be clear that both instability and hyperactivity must be always studied, and robust solutions are already described in (Pacheco 1999).

Technology

OPS systems are based on well-known technology. The main elements are the organic anchorages, the unbounded tendons, and the electronic circuit. All of them have been used with reliable results (see Fig. 6). Obviously, the prestressing cables must be unbounded.

The design and construction technologies are similar to the ones required in post-tensioned unbounded prestressing structures, but special attention must be given to fatigue and fretting fatigue (Pacheco 1999).

Organic anchorages are anchorages with servo-hydraulic systems incorporated. That means that the jacks stand between the anchorage and the structure (see Fig. 7). The electronic circuit includes sensors, electric cables and electronic components, and is very similar (Pacheco 1999) to common active control system circuits (see Fig. 8).

Of course, safety measures are essential. Emergence supplying units and redundant safety systems ought to be considered. Basic rules and main criteria are already studied for some applications (Pacheco 1999).

Example

The following example provides a synthetic explanation of OPS behavior and corresponds to a real design problem. This was previously presented (Pacheco et al. 1997a) but later was redesigned to achieve a better fatigue performance (Pacheco 1999). It consists of two parallel viaducts flying over a road junction and located on top of an underground metro station (see Figs. 9 and 10). High cost of alternative in steel, requirement of minimum free

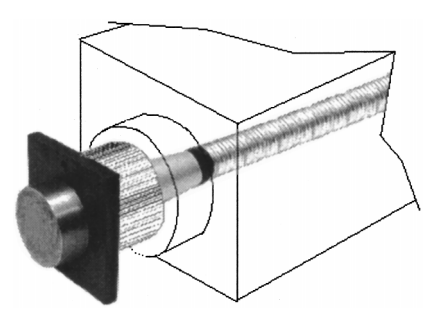

Fig. 7. Organic anchorage

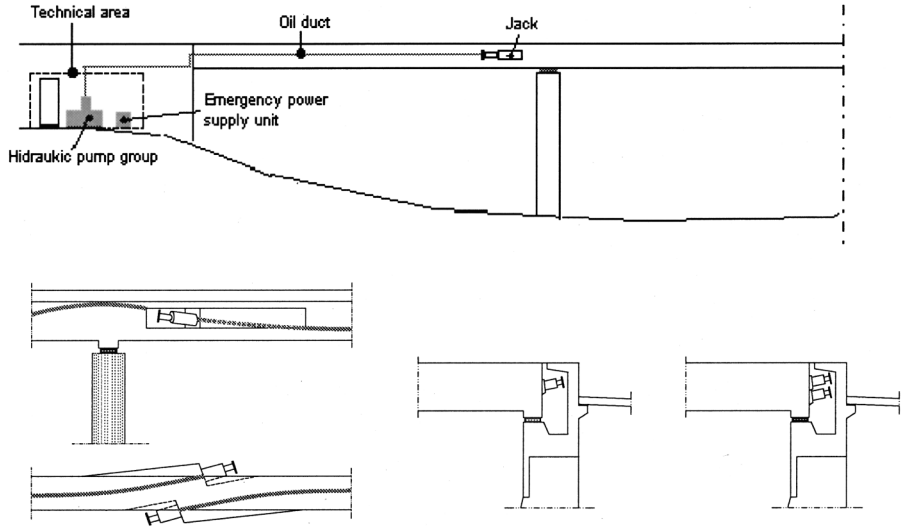

Fig. 8. Details of structures with OPS systems

height, and the need for the lightest structure, meant a prestressed concrete box girder solution was adopted. This design was optimized with a 1.50 m constant depth box girder and a global conventional longitudinal prestressing of 6,015,750 kN m.

For identical loads and design criteria, both taken from several texts and codes of practice [OHBDC 1983; Menn 1986; ACI 1993; REBAP 1993; Eurocode 2 1994; FIP 1998), the alternative nonconventional, that is, organic, prestressing leads to a lighter box girder of 1.35 m constant depth with a global longitudinal prestressing of 6,175,125 kN m (2.6% more than conventional prestressing), of which 27% are OPS. OPS prestressing design requires the consideration of the ultimate limit state of resistance with the accidental load of OPS failure.

The prestressing losses are greatly reduced because in OPS the permanent prestressing forces are of small value. Furthermore, other losses can be partially compensated by increasing the stressing forces on the OPS cables (see Fig. 11).

It should be clear that, under these conditions, the cross section of the OPS solution (with 23% inertia reduction) with conventional prestressing does not satisfy the design criteria.

Diverse loading cases are considered with combinations of moving loads and distributed continuous loadings. Moving loads are more relevant because the OPS delay is quite insignificant with distributed continuous loadings.

Figure 12 represents permanent and maximum stresses at bottom fibers under the first load and contractions of all organic cables for a loading case with a three axle vehicle (3×200 kN) moving from left to right at a speed of 13.89 m/s (50 km/h). Delay in response of the OPS and interactivity explain the nonsymmetry of the *nc* curves.

The OPS solution leads to similar minimum compression values, as shown in Figs. 13 and 14, but the following parameters have to be addressed most carefully: (1) fatigue damage in organic cables; (2) deformations; (3) vibrations.

The maximum deflection for the OPS solution (17 mm) is smaller than for the conventional one (20 mm), but they are both acceptable ($\Delta=L/1934$ and $\Delta=L/1724$, respectively). The same happens with vibrations. According to the Rausch method (Menn 1986), both solutions fall within Class A (Classes A, B, C, and D are acceptable). Fatigue control is performed by a cumulative calculation of damage according to Palmgreen-Miner's rule (Eurocode 2 1994). This damage results from the stress variations on the organic cables that are generated when contraction/release cycles take place. Figure 15 shows that no organic cable requires replacement after 20 years of service and some of them should be able to remain in service for further decades.

Conclusions

OPS solutions can be designed with simple and efficient control strategies. Increase of slenderness and reduction of structural ma-

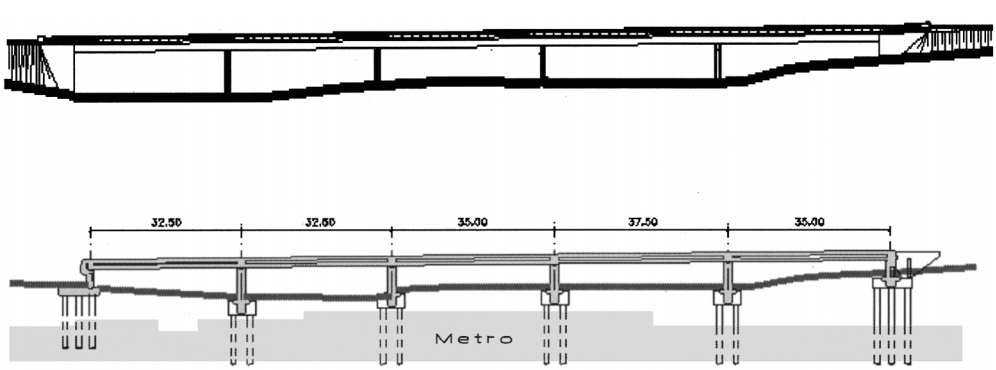

Fig. 9. Elevation and longitudinal section of viaducts

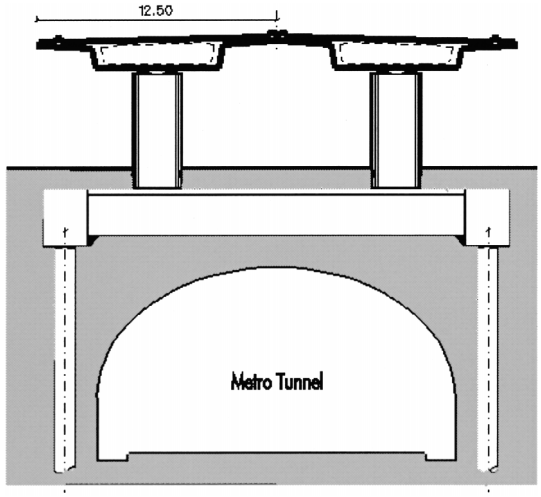

Fig. 10. Cross section of viaducts

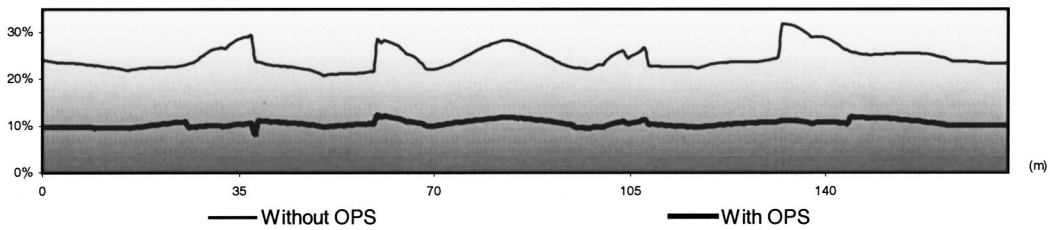

Fig. 11. Total prestressing losses

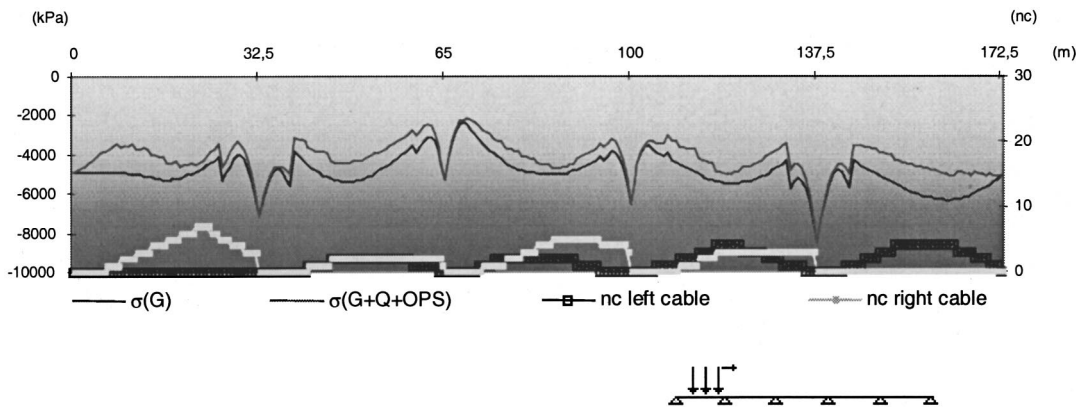

Fig. 12. Stresses at bottom fibers and organic cables contractions with three axle vehicle loading case

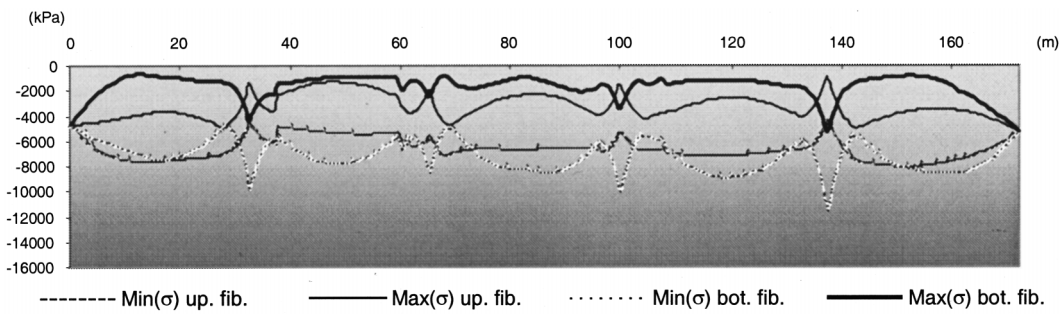

Fig. 13. Maximum stresses at upper and bottom fibers without OPS

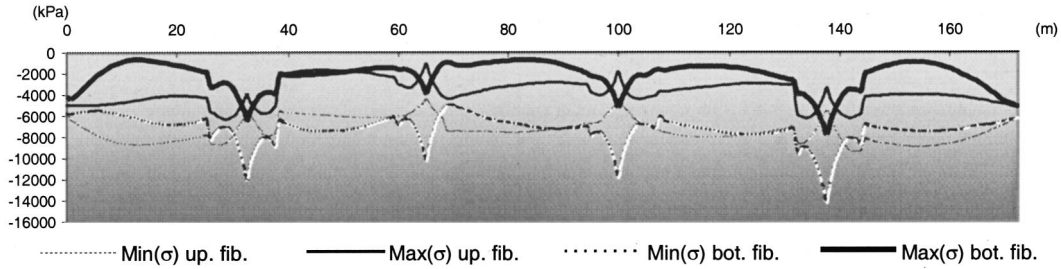

Fig. 14. Maximum stresses at upper and bottom fibres with OPS

terial can be achieved using the same quantity of prestressing and maintaining the same levels of structural performances. Furthermore, OPS allow higher prestressing under variable loads without implying unacceptable levels of creep.

Deformations, vibrations and fatigue damage have to be controlled most carefully but should not imply major difficulties. The great reduction of prestressing losses (of about 50%) and the organic control allow 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 envisaged.

The research on organic prestressing is at an early stage and various applications are being studied, some with even better results (when ''live-load/dead-load'' ratios are higher). The experimental research is now starting at Oporto University and will stimulate further knowledge.

Notation

The following symbols are used in this paper:

C = interactivity coefficient;
G,Q = dead loading; live loading;
h = loading history
I = interactivity mode;
j or OPS = OPS system;
k = loading phase;
M_{ac} = activity matrix;
n_{OC} = number of organic cables;
nc = number of active contractions;
Sci or i = control section (relevant fiber in control cross section);
t = instant t;
$[V_a^I]$ = activity vector in I interactivity mode;
$[\overline{V}_{TT}]$ = vector of stress increments;
Δ = span/deflection ratio;
Δ_a = activity margin;
Δ_c = compression margin;
Δt = time step;
δ = incertainty;
ϕ_I = modal contribution factor;
σ = stress;
σ_I^* = stress increment for contraction in I interactivity mode;
σ^{INT} = interactive stress increment; and
$\overline{\sigma}$ = stress increment.

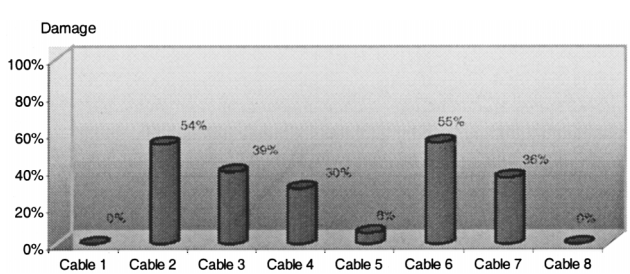

Fig. 15. Fatigue damage on organic cables after 20 years

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