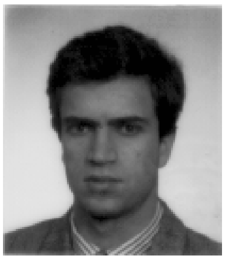
ORGANIC PRESTRESSING – AN EXAMPLE OF AN EFFECTOR SYSTEM



AUTHOR
Pedro Álvares Ribeiro do Carmo Pacheco

SUMMARY

The extraordinary efficiency of some structural solutions found in Nature may help structural engineers in the development of new structural solutions, specially now that a remarkable technological evolution allows for sophisticated applications to be implemented. Commonly, the increase in resistance of a structural element is understood to imply either a different geometry of its cross-section or a different structural material. And that has to be done on a permanent basis.

An effector system or "artificial muscle" is a structural element with the capacity of modifying the strength of a structure (by an adequate supplying of energy), thus improving conveniently its performance. An effector system may be regarded as an active control system that is also a structural element, with applications extending to scenarios of *quasi-static* loading.

Organic prestressing is an example of effector system that is feasible within the present technological capacities. In fact, it is none else than a prestressing system under *on-line* control, with the capacity to increase/decrease the prestressing forces introduced in the cables, thus improving significantly the prestressing effect.

This paper presents, very synthetically, some of the main subjects developed in the PhD Thesis (with the same title and in Portuguese) submitted in 1999 to the Faculty of Engineering of the University of Oporto, Portugal.

INTRODUCTION

New concepts of active structural control were developed at the end of last decade under the names of "parastressing"[7] and of "effector systems"[8]. Both involve active control systems[14] where actuators are not external supplementary elements, rather are structural elements themselves. Freyssinet and Zetlin had investigated also along these ideas some 40 years ago. Most probably, these two remarkable structural engineers did not proceed with their research because the technological context of their time was unhelpful.

A useful example of effector system is provided by organic prestressing systems (OPS), which have been object of several numerical applications[8, 9,10,11,12]. A prototype is now on its first steps of execution, but its resilience offers no doubt, since OPS make use of well-known technologies.

OPS result in an "optimised" prestressing, because permanent undesirable stresses are avoided and prestressing time-dependent losses are greatly reduced. Furthermore, OPS allow 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.

In this paper, a synthetic and general approach to structural solutions of bio-structures is presented. Also, a brief description of the muscular contraction is called to emphasize the concept of effector system. Then, the methodology to implement OPS is presented together with the mathematical expressions in the algorithms of an efficient control strategy. Finally, examples of applications are provided and main conclusions of this research are put forward.

BIO-STRUCTURES

An immense variety of structural solutions exist in the bio-structures world. Some are simple and others are quite sophisticated. All are sources of rewarding research. Structural engineers will certainly identify some well known structural elements. Although shapes may differ, structural objectives are the same. Nevertheless, some simple calculations show that the “design criteria” in bio-structures is quite different from those in Civil Engineering. Obviously, the “auto-repair” capacity of living materials is a major feature of bio-structures.

In Table 1, four bio-structural elements very similar to common structural elements are shown. But up to now, no structural element in structural engineering could play the role of a muscle in a bio-structure. True, there are some features in active control systems that resemble muscles, but the latter are structural elements themselves.

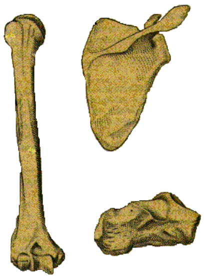
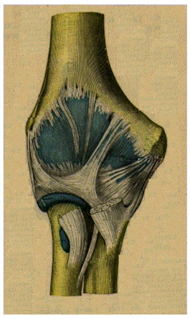
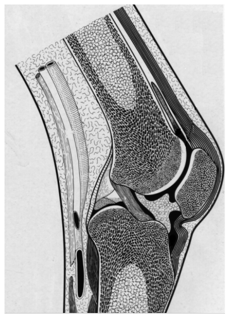
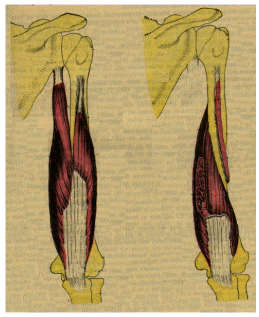
				
BONES	**LIGAMENTOUS**	**ARTICULAR CARTILAGE**	**TENDONS**	**MUSCLES**
STRUTS, COLUMNS, BEAMS AND SHELLS	**CONNECTORS**	**BEARINGS**	**TIES AND CABLES**	**EFFECTOR SYSTEMS**

Table 1 – Main structural elements in animal bio-structures[2, 3,11,15]

A muscle is a structural element with a variable stiffness. That change of stiffness is achieved by supplying energy. Therefore, a muscle – or an effector system - can be regarded as a structural element that gets stiffness out of energy. In other words, a muscle is a string with variable stiffness.

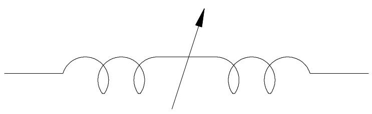


Figure 1 – Representation of an Effector System – string of variable stiffness

Since the beginning of the 20th century, researchers from different areas of knowledge have been able to identify many structural systems and structural features of bio-structures [1,2,3,4,5,13,15]. The contributions of D´Arcy Thompson and Hildebrand is emphasized, but the contribution of structural engineers is fundamental if meaningful conclusions are to be drawn from that specific research area.

In Table 2, some classical examples of structural systems are displayed, together with more complex systems where muscles play a structural function.

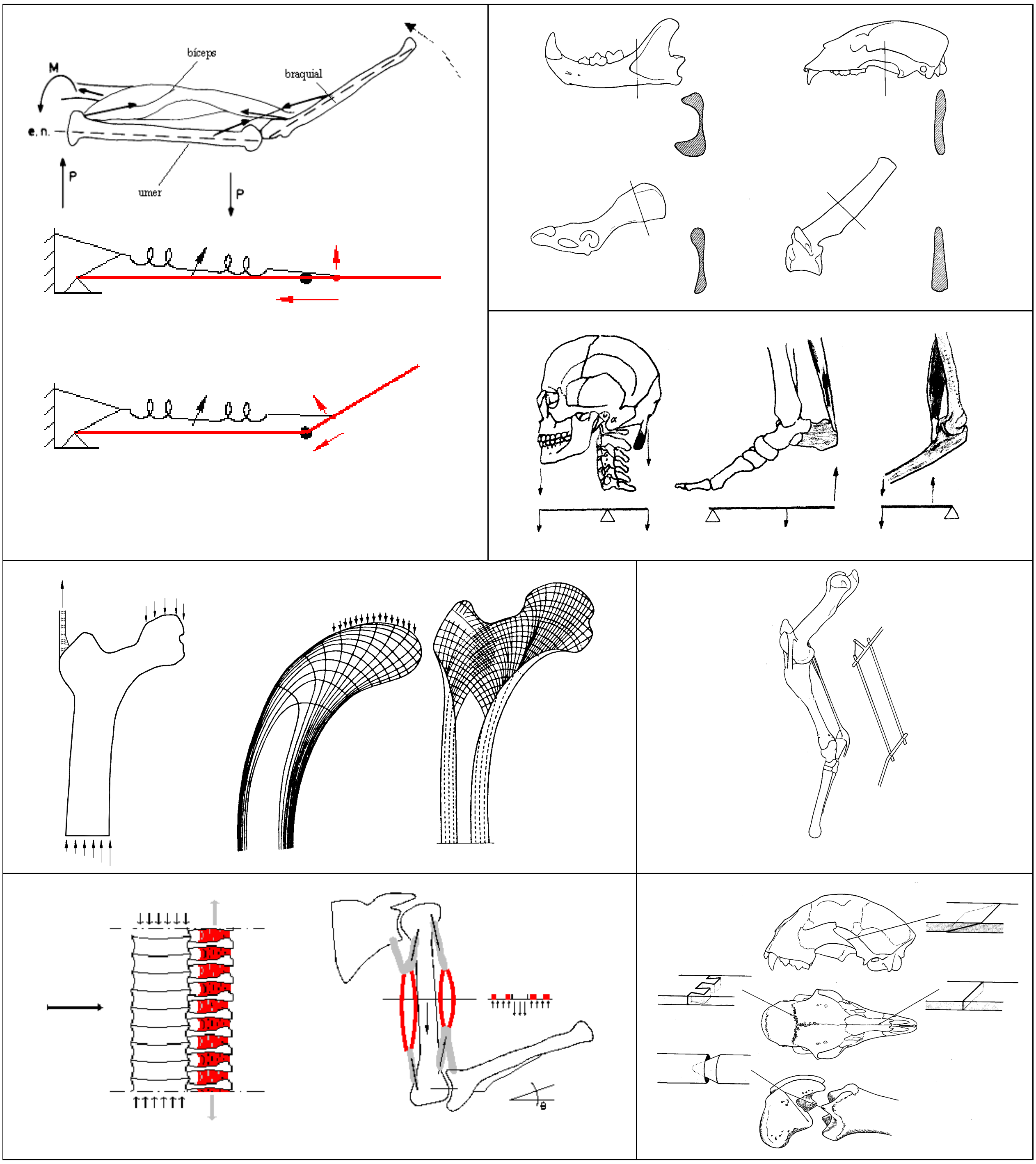


Table 2 – Examples of structural systems in bio-structures [3,5,11,15]

Many "lessons" can be learned from all those amazing structural systems. And it is quite obvious that muscles provide a "special" prestressing, which avoids the undesirable stresses that are implied in conventional prestressing. And that "special" prestressing is more efficient because it is variable, only acting when required.

EFFECTOR SYSTEMS

Construction materials have always been taken as stable materials, with constant properties. Any sensibility to environmental changes is regarded as undesirable and variations of behaviour are taken as external actions[8].

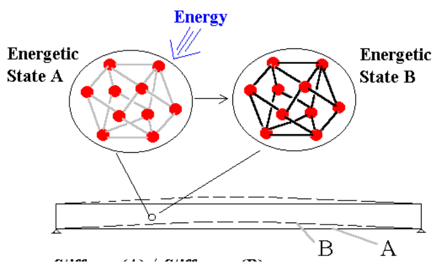


Figure 2 - Stiffness change by energy induction

Some variations involving transfer of energy can, nevertheless, be dealt with in a different way. Also, since the elasticity modulus of all materials depend upon their energetic state, control and modification of the latter implies control and modification of the former.

This leads to two trivial questions: How can it be done? What structural advantage can be taken out of it ?

In the case of *sensory* or *adaptative* materials, this is achieved by direct induction[14]. Otherwise, *energy transformers* have to be used for an indirect induction. Energy transformers are to be taken as mechanisms introducing elastic energy into a structure out of other forms of energy. Hydraulic jacks and electromagnets are examples of energy transformers.

The best answer for the second question is in Nature. Muscles are structural elements whose microscopic units are the sarcomers. These organic units are made of two kind of proteins: actin and miosin.

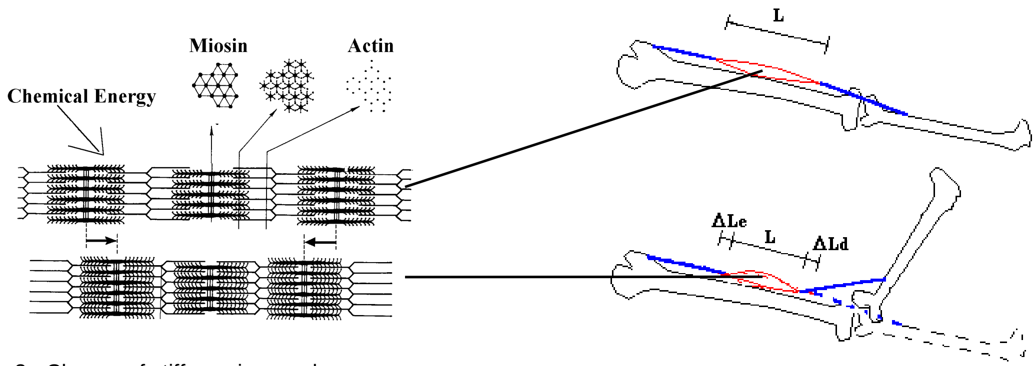


Figure 3 - Change of stiffness in muscles

When a contraction “decision” is taken, a chemical energy induction takes place, providing a relative displacement of actin and miosin that changes the sarcomers configuration. This process alters the muscle elasticity modulus and modifies the stress state of the structure where the muscle is included. This “effector system” ensures no undesirable stress states are generated in the bones, thus improving the structural performance of such a biomechanic structure.

An effector system or “artificial muscle” is a structural element with the capacity of modifying the strength of a structure (by adequate energy supply) improving conveniently its performance, typically whilst under specific actions.

One possible answer to the first question is the Organic Prestressing System (OPS).

ORGANIC PRESTRESSING

Organic prestressing is a stress-triggered self adjusting prestressing system. This system is based on well-known technology. The main elements are the organic anchorages, the tendons and the electronic circuit. All of them are widely used with reliable results. Obviously, the prestressing cables must be unbounded.

Their design and construction technologies are similar to those required in post-tensioned unbounded prestressing structures, and the electronic circuit, which includes sensors, electric cables and electronic components, is very similar[11] to a common active control system circuit.

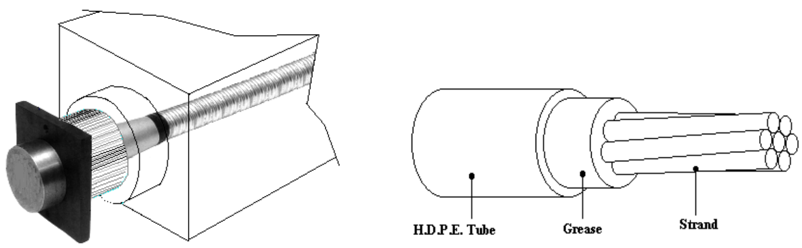


Figure 4 - Organic anchorage, unbounded tendon and typical layout of prestressing cable for a simply supported beam

Organic anchorages are anchorages with servo-hydraulic systems incorporated. That means that the jacks stand between the anchorage and the structure.

The control strategy is very simple[8,9,11]. It is based on an algorithm quite similar to the classic "on-off" algorithm. In short, if compression is low, OPS produces "contractions" (prestressing forces are amplified), and if compression is high, OPS produces "descontractions" (prestressing forces are reduced). In mathematical terms, this is stated by expression (1):

$$\begin{cases} \Delta_{ai} < \sigma_{Sci}(G) + \sigma^{t}_{Sci}(Q) + nc_t \times \overline{\sigma}^{OPS}_{Sci} < \Delta_{ci} & \Rightarrow \quad nc_{t+\Delta t} = nc_t \\ \sigma_{Sci}(G) + \sigma^{t}_{Sci}(Q) + nc_t \times \overline{\sigma}^{OPS}_{Sci} > \Delta_{ci} & \Rightarrow \quad nc_{t+\Delta t} = nc_t + 1 \\ \sigma_{Sci}(G) + \sigma^{t}_{Sci}(Q) + nc_t \times \overline{\sigma}^{OPS}_{Sci} < \Delta_{ai} & \Rightarrow \quad nc_{t+\Delta t} = nc_t - 1 \end{cases} \qquad (1)$$

where,

σ_{Sci} *(G)*	is the stress at the relevant fibre in control cross section *i* due to dead loading;
σ^{t}_{Sci} *(Q)*	is the stress at the relevant fibre in control cross section *i* due to live loading at instant *t*;
$\overline{\sigma}^{OPS}_{Sci}$	is the stress increment at the relevant fibre in control cross section *i* produced by one contraction;
nc_t and $nc_{t+\Delta t}$	are the number of active contractions at instants *t* and *t*+Δt.
$nc_t \times \overline{\sigma}^{OPS}_{Sci}$	is the stress at the relevant fibre in control cross 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);

The generalisation of this algorithm to continuous beams is established in a similar manner[11]. 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 logical procedures implicit in the mathematical expressions. This is explained with all detail in reference 11.

Numerical analysis involves several aspects:

- calculation of prestressing losses taking into account the particular properties of organic prestressing;
- definition of realistic evolutive loadings whose effects are at least equivalent to those defined in design codes;
- analysis of control specific problems through adequate mathematical models;
- analysis of uncertainties;
- fatigue damage assessment and consideration of fretting fatigue;
- ultimate and service limit states assessments (based on conventional procedures);
- dynamic analysis including the control action dynamic effects;
- definition of reliability procedures in design and in construction (emergence supplying units, redundant safety systems etc).

Those issues are already studied[8,9,10,11,12], but testing by experimental analysis is required. That is the goal of the present stage of this research.

The control effect produced by OPS may be understood in figure 4, which refers to a loading case on the structure of the first example presented in Examples, where 8 OPS cables are implemented (two in each intermedium span and one in each extreme span).

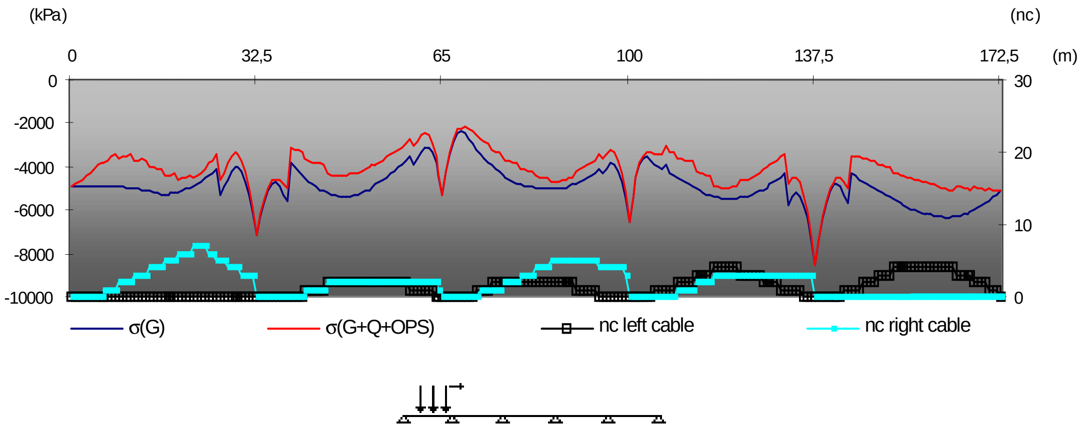


Figure 5 - Stresses at bottom fibres and organic cables contractions under a three axle vehicle loading case[12]

One of the most important features of OPS is the fact that the prestressing loses are greatly reduced. Because the hydraulic jacks are incorporated into the structure, they can compensate instantaneous losses. On the other hand, time dependent losses are relevant only in the permanent component of prestressing. In the example referred before, the difference found in two distinct solutions developed for the viaduct, one with OPS and one other without OPS, is quite obvious.

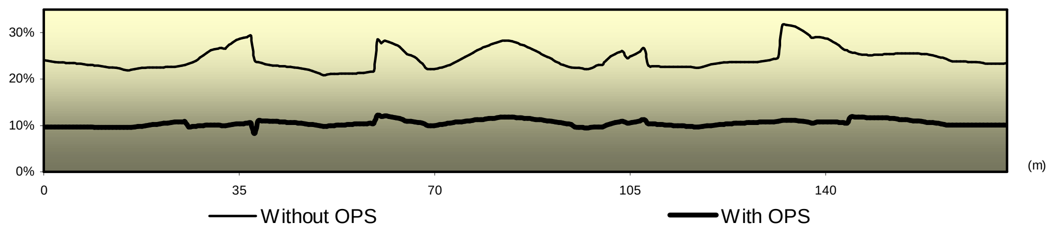


Figure 6 - Total prestressing losses[12]

Another relevant aspect of OPS is related with the cross-section design of the structural elements. The value of the prestressing force in a prestressed structural element has to fall inside an interval implied by conditions expressing the design specifications. An empty interval requires an increase in the size of the cross-section or a new conception of the structure. That situation, which is relatively common in conventional prestressing design, does not exist in organic prestressing design (or is extremely reduced), because prestressing forces are never too high.

At the present stage of knowledge, the following balance of benefits/difficulties can be stated as follows:

Advantages of OPS:

- 50% reduction of prestressing losses[8,9,11];
- For slow loadings – until 70% reduction of stiffness[8,9,11];
- For slow loadings – until 30% reduction of structural mass[8,9,11];
- Lower permanent stresses[11];
- Lower deflections[11];
- Lower creep deformations[11];

Issues demanding special care:

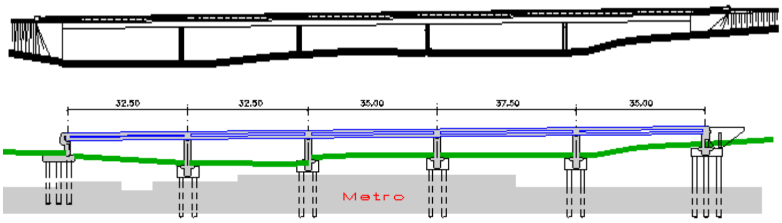
- Fatigue[9];
- Dynamic effects[11];
- Cost (powerful pumps for “fast” loadings)[11];
- Hyperactivity (control system)[12];
- Instability (control system) [12].
- Reliability [12].

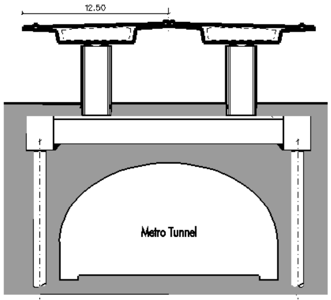
There are consistent procedures to overcome most of the difficulties[11,12], but fot the proposed methodology, applications with fast loadings imply powerful pumps and may imply dynamic problems. Obviously, before further developments, the OPS application field must reflect this, and in the next steps of research, structures with “slow” loadings will be considered.

EXAMPLES

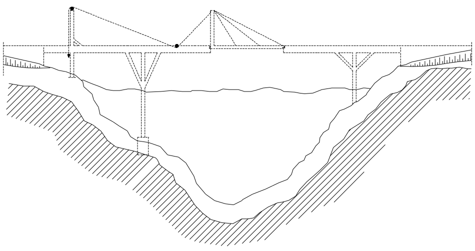
Several examples have been studied. In same examples, although structural advantages are recognized, difficulties (mentioned before) do exist (using only well-known technologies). In other cases, there are strong reasons to develop their applications. Typically, better results were found in structures with high “live load / dead load” ratios and with relatively “slow” loadings[10,11,12].

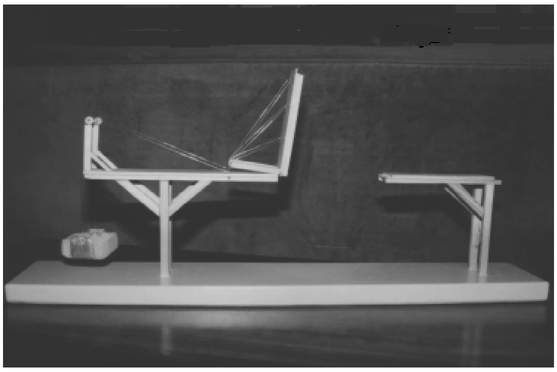
At the present technological capacities. one of the most promising applications is on launching gantries.



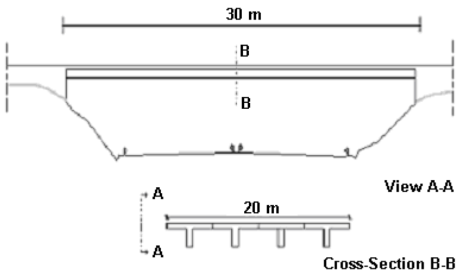


Urban Viaducts with strong conditionalisms of slenderness and weight with OPS[9]

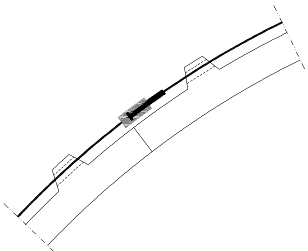




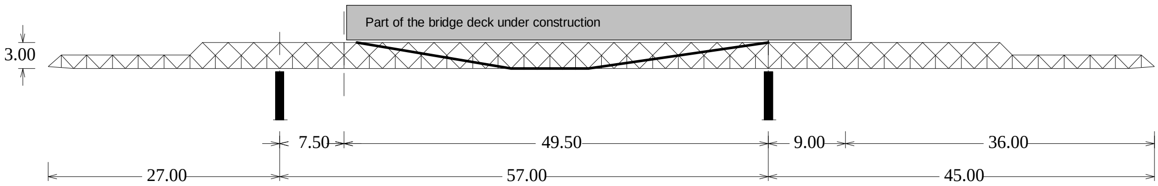
Organic Prestressing associated with locomotion functions[11]



Current road bridge with OPS[8]



Precast concrete Silos designed with Snoko System with OPS[6,11]



Launching Gantry with OPS[10,11]

Table 3 – Organic prestressing applications

CONCLUSIONS

The implementation of structural solutions of Nature into engineering structures is a research field of immense interest. The modification of structural stiffness by the induction of energy is a subject that it is in its infancy, but it should be accepted that the concept of effector system (or artificial muscle) opens new frontiers to the conceptual design of structures.

Organic prestressing is one example which exhibits remarkable potentialities, specially when lightness and slenderness are desired. The theoretical aspects of the organic prestressing design are already developed and numerical results sustain its potentialities. The great reduction of permanent compressions and prestressing losses allow for a more rational use of prestressing.

In structures with high live-load/dead-load ratios and with slow loading actions, organic prestressing can be a success, but experimental research is essential at this stage of knowledge and it is already in its beginning.

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NOTATION

The following symbols are used in this paper:

G,Q	= dead loading; live loading;
OPS	= OPS system;
nc	= number of active contractions;
Sci or i	= control section (relevant fibre in control cross section);
t	= instant t;
Δ_a	= activity margin;
Δ_c	= compression margin;
Δt	= time step;
σ	= stress;
$\overline{\sigma}$	= stress increment;