Effector Systems in Structures

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1. ABSTRACT

Basic concepts of structures with variable elasticity modulus are presented. A biostructure system is briefly described to illustrate the structural potentialities of materials with variable elasticity modulus. The concepts of effector system and organic structure are also defined.

The modification of structural stiffness by the induction of energy is considered, and a brief description and examples of its implementation are presented. Solutions by energy transformers and solutions by adaptative materials are described.

The organic prestressing system (OPS) is presented as an example of effector system. The corresponding model is characterised and OPS solutions are compared with conventional prestressing ones. A computer program for the analysis of OPS structures is also described and examples are studied, specifically having in mind the design of bridge decks.

Finally, results are discussed and conclusions are drawn.

2- INTRODUCTION

Research on “Conceptual Design of Structures - from Nature to Engineering” soon leads to the “cleverness” of biostructures. Its implementation into engineering structures is then a research field of immense value.

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 improving conveniently its perfomance temporary, typically whilst under specific actions. An effector system may be regarded as an active control system (ACS) which is also a structural element and with applications extending to scenarios of *pseudo-static* or *quasi-static* loading.

A structural element with “variable prestressing” or “organic prestressing” is one example of effector system that can be implemented within the present technological context. Jacks are incorporated in the prestressing cable anchorages and respond to stress sensors strategically located along the structure. The structural perfomance is improved both because prestressing becomes “intelligent” and because rheological prestressing losses decrease significantly.

3- BASIC CONSIDERATIONS

Construction materials have always been taken as stable materials, with constant properties. Any sensibility to environmental changes was regarded as undesirable and variations of behaviour were taken as external actions.

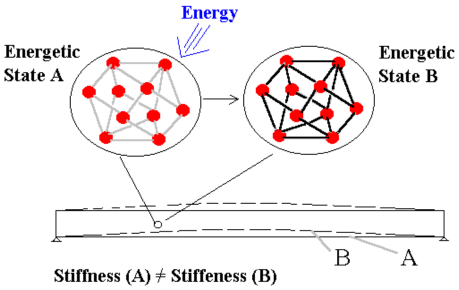

Figure 1 - Stiffness changes by energy induction

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. 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 others forms of energy. Hydraulic jacks and electromagnets are examples of energy transformers.

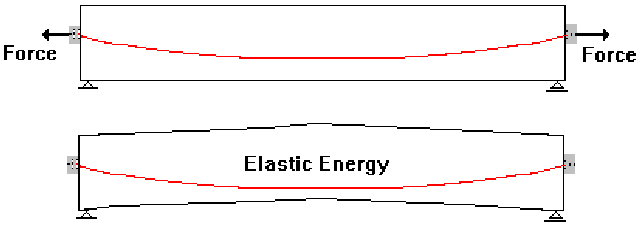

Figure 2 - Energy indirect induction

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.

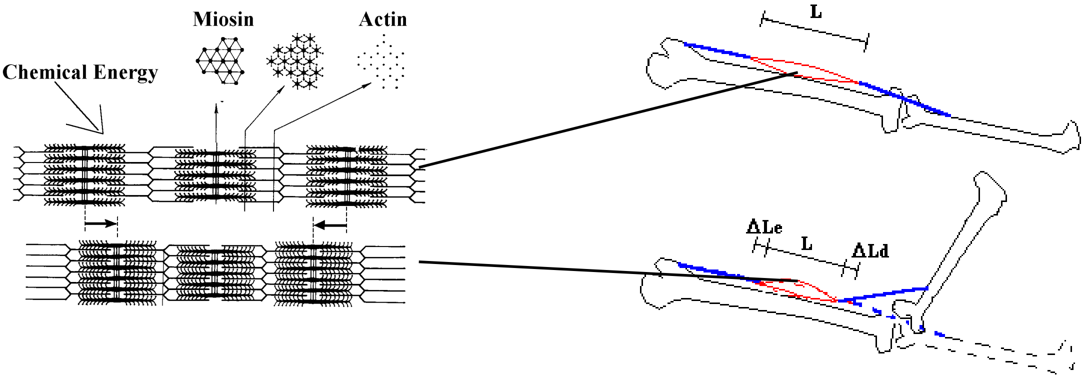

Figure 3 - Change of stiffness of the muscles

(*) Adaptative or sensory materials are materials with the capacity of exhibiting significant deformations (about 10^-3) without being acted upon by any kind of mechanical actions, i. e., being acted only by energy induction [S3]. Piezoelectric materials are one example of adaptative materials.

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 perfomance of such a biomechanic structure.

An effector system or "artifitial muscle" can be defined as an active control system in which the actuator is a structural element and whose activity provides efficiency both under *quasi-static* and dynamic loading.

An organic structure is any structure incorporating at least one effector system. An organic structure has the capacity of adapting the structural behaviour to the acting loads. For instance, the human arm is an organic structure where the humerus exhibits values of eccentricities typical in beams or typical in columns, as the loads take low or high values [P1, R1].

4 -ORGANIC PRESTRESSING SYSTEMS - AN EXAMPLE OF EFFECTOR SYSTEM

The value of the prestressing force in a prestressed structural element has to fall inside an interval defined by conditions stating the design specifications. An empty interval may imply an increase in the size of the cross-section or a new conception of the structure. Alternatively, the use of effector systems may prove to be successful. For example, a variable prestressing system, or organic prestressing system (OPS) is capable of modifying the value of that prestressing force, depending on the loading acting on the structure.

In a similar manner, some active control systems use active cables as actuators [A2, A3, C3, F1, L3, Y1]. Freyssinet and Zetlin have also investigated along these ideas some 40 years ago. Most probably, these two remarkable structural engineers did not proceed on their research because the technological context of their time was unhelpful.

From 1970 onwards, active control systems were developed in order to control vibrations and other dynamic effects, and tests have been implemented both in experimental models and in some

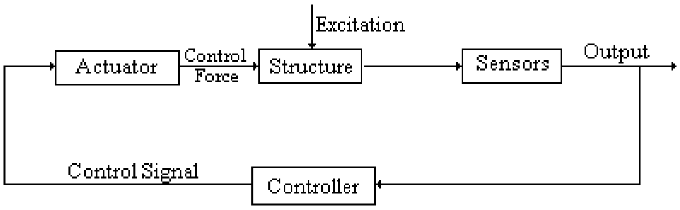

Figure 5.A - ACS control circuit [F1]

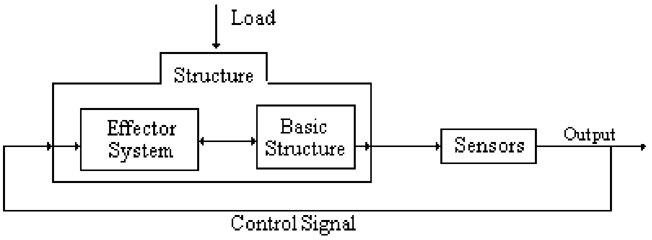

Figure 5.B - OPS control circuit

(*)The expression "Effector Unity" was used by Silva [S1] to describe an experimental model of artifitial muscle buildings or bridges. But control strategies are complex, large forces with high frequencies are difficult to activate and costs are high [F1,Y1].

Generally, variable prestressing overcomes those first two difficulties. The control strategy is simple and requires no controller, and frequencies of acting loads are low. The simplicity of the control strategy results from the easier prediction of static quantities. Consequently, control circuits for ACS and for OPS differ, as shown in Figures 5.A and 5.B.

4.1. Design of an organically prestressed beam

Designing an organically prestressed beam implies the definition of all conventional parameters (geometry, materials, cables layouts, etc.), of the control strategy and of the relevant mechanical parameters characterising the organic anchorages, such as the power of the pumps or the velocity of the pulling cylinder.

The main elements of an organically prestressed girder are schematically represented on the following figure.

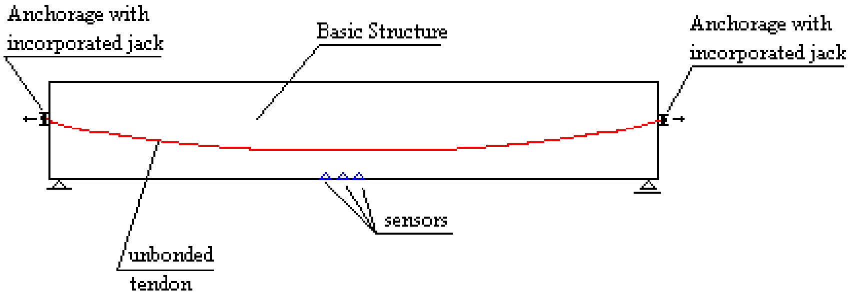

Figure 4 - OPS structure

In the examples that are being studied, the control strategy is implemented though actuators acting when predefined stress limits are reached in critical sections, and it has been designated c*ontrol by stress sensoring on critical sections* [P2].

The values of the predefined stress limits must take into account the delay of the response of the system. This is achieved by the introduction of a *compression margin* (σi_c) in each critical section. As it is shown in Figure 6, even if a significant delay of the system response cannot be avoided, the compression margin ensures no tensile stresses will be generated. Obviously, a more powerful jack means a more efficient system and, consequently, predefined stress limits can approximate the design values used in conventional prestressing. Fatigue problems of the organic cables are reduced if they are activated only when the structure is submitted live loads greater than predefined values (Q_{act}).

The "contraction process" may imply successive stress increments ($\Delta\sigma_{ops}$) of the prestressing cables, eventually till the maximum capacity of the mechanic system is reached, for predefined values of the live loads (Q_{lim}). But higher loads can be resisted by the structure, either with the organic cables taking the role of conventional unbonded tendons or with further contractions being implemented on the cables. In this last case the ultimate resistance of the beam increases significantly.

This can be understood in the diagram presented in Figure 6 (where P_f and P_{ops} are the prestressing forces of the fixed and organic systems respectively, and σ_{s1} and σ_{i1} are the stresses at the top and at the bottom of the critical section, also respectively).

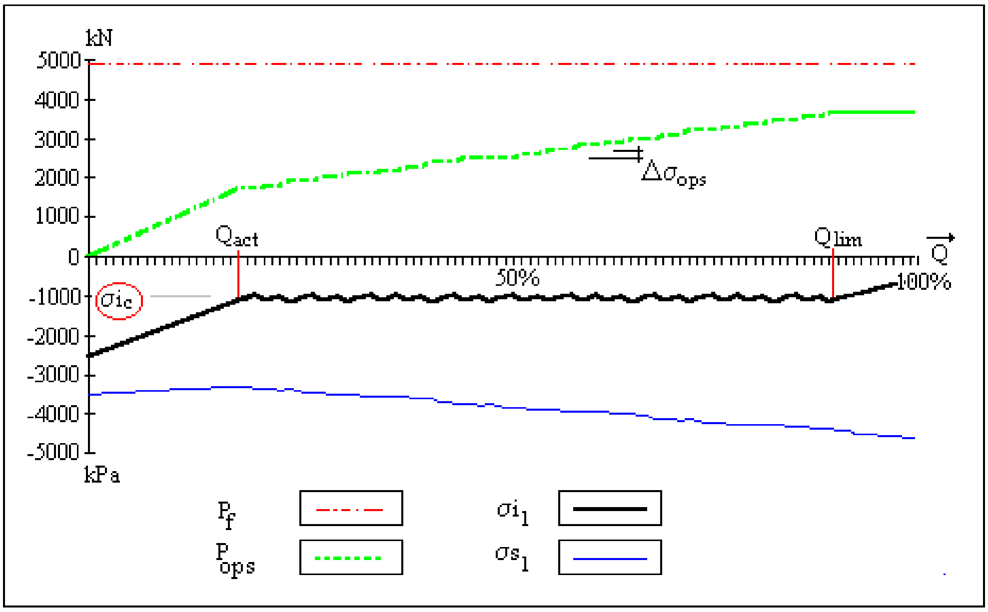

Figure 6 - Stress-Live loading- prestressing force diagram on a control section for a monotonous increasing loading

4.2 - Comparison of a conventional solution with three alternatives using OPS

A road bridge of one single span of 30 m is now taken as an example. The deck is made up of T beams simply supported on the abutments, as shown in Figure 7. A computer code was developed and provides the design of all parameters, including those defining the mechanical devices operating the variable prestressing cables.

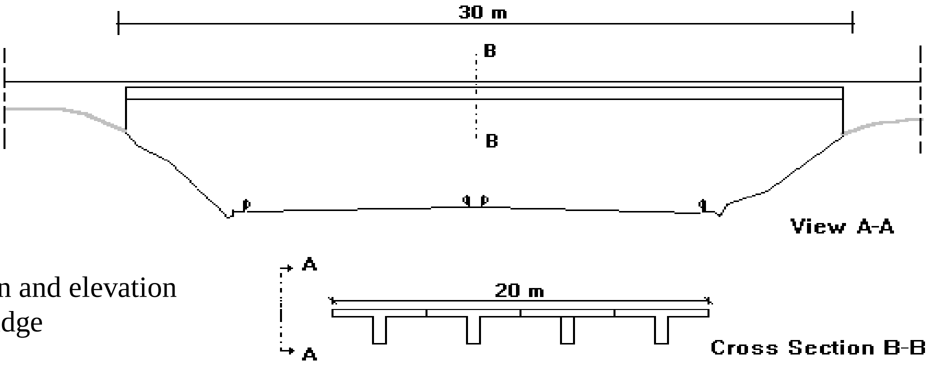

Fig. 7 - Cross-section and elevation of the bridge

Four solutions were implemented, as described in Table 1.

Solution A:	Conventionally Prestressed
Solution B:	Same dimensions as Solution A, but organically prestressed.
Solution C:	Solution with a thinner beam and organically prestressed
Solution D:	Solution with both dimensions smaller than in Solution A and organically prestressed

Table 1 - Description of the four solutions

Structural materials, loads and limit states of design are equal for all solutions.

4.2.1 Limit States of Design

The beam dimensions and the prestressing values (conventional and organic) are defined in order to verify the following limit states, in all cases:

1 -	All sections under compression for 100% of live load
2 -	No compression stresses greater than $0.6.f_{ck},t_1$ when prestressing is applied (where f_{ck},t_1 is the compression ultimate resistance of concrete at instant t_1 after casting)
3 -	No compression stresses greater than 0.45 f_{ck} when 20% of live load is applied (where f_{ck} is the concrete maximum ultimate resistance)
4 -	No compression stresses greater than 0.6 f_{ck} when 100% of live load is applied
5 -	Deformations Δ under dead load less than (l/750)
6 -	Fatigue limit state for an equivalent vehicle of 220 kN [A1]
7 -	Vibrations induced by vehicles *acceptable* [M1]
8 -	Ultimate Limit States of Flexion and Shear

Table 2 - Limit states of design

These criteria were selected from several international codes and textbooks [A2, E2, F2, M1, O1 e R2].

4.2.3 Data

All beams are of constant cross-section and with geometric properties shown in Table 3. Structural material are as follows:

Concrete - f_{ck}= 23.3 MPa E_c= 33.5 GPa
Ordinary steel - f_{yk}=348 MPa E_s= 210 GPa
Prestressing steel - f_p= 1860 MPa E_p= 200 GPa

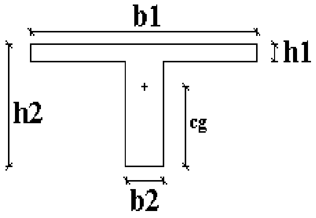

Fig. 8 - Beam Dimensions

Live loading was taken according to the Portuguese Code [R5].

Dimensions	Solution A	Solution B	Solution C	Solution D
b1 (m)	5	5	5	5
b2 (m)	0.75	0.75	0.45	0.45
h1 (m)	0.25	0.25	0.25	0.25
h2 (m)	2	2	2	1.5
A (m2)	2.5625	2.5625	2.0375	1.8125
I (m4)	0.9817	0.9817	0.6906	0.298

Table 3 - Dimensions of the four solutions

Special attention was given to the fatigue limit state, due to the important stress amplitudes in the organic tendons, and to the vibrations limit state, because OPS structures tend to be more flexible.

4.2.4 Results

		Solution A	Solution B	Solution C	Solution D
Pef (kN)	Fixed Prest.	11000	2000	1400	2200
Pops (kN)	Organic Prestressing	0	5200+27*100	4200+23*100	4750+34*100
P_{ao} (CV)	Pump Power	0	86	96	186
Apt (mm2)	Tot. Prest. sect.	**7885**	**7097**	**5663**	**7419**
Pef+Po+nc*Pops (kN)	Total Prestr. pull	**11000**	**9900**	**7900**	**10350**
Total Losses	--------------------	**23.54%**	**10.59%**	**10.57%**	**10.86%**
Total Weight (kN)	------------------------	**1921**	**1921**	**1528**	**1359**

Table 4 - OPS program outputs

Solution B (with the same beam dimensions of solution A) allows a reduction of 10% of the total applied prestressing. That happens because prestressing losses in Solution B are half of prestressing losses in solution A. Solution C exhibits values of losses which are similar to the values in Solution B, but, as it is a lighter solution, it requires a lower prestressing force (about 28% less than in Solution A).

Solution D corresponds to slender (less 25%) and lighter (less 30%) beams, with a maximum prestressing force which is lower than the prestressing force in Solution A.

5. CONCLUSIONS

Effector systems open new frontiers to the conceptual design of structures, and organic prestressing exhibits remarkable potentialities, with a significant structural economy in cases where the prestressing degree is very high. A more logical relationship between the stress levels is achieved, greatly reducing permanent compressions and prestressing losses. Clearly, organic prestressing systems provide useful solutions for improving the structural perfomance of prestressed structures.

References

A1 **A.A.S.H.T.O - Standard Specifications for Highway Bridges ,** 1992

A2 **Abdel-Rohman M, Leipholz H.H.E.,** “Active Control of Tall Buildings”, Journal of Structural Engineering, ASCE, Vol. 109, Nº 3, pags. 628-645, 1983

A3 **Abdel-Rohman M,** “Active Control of Large Structures”, Journal of Eng. Mech. Division, ASCE, Vol. 108, Nº EM5, pags. 719-730,1982

A4 **ACI - Part-4 (Manual of Concrete Practice),** “Bridge Analisys and Design”, (5.7.6. - Fatigue), (pp 343R-67), 1993

C1 **CEB-FIP Model Code 1990,** Bulletin D´information Nº 204**,** “ 4 - Data for Prestressing”, 1991

C2 **CEB,** Bulletin D´Information Nº 209, “Vibtration Problems in Structures”, 1991

E1 **Eurocode 2,** prENV Part 1-5, “The use of unbonded and external tendons”, (Final Draft), 1993

E2 **Eurocode 2,** ENV 1992 “Design of Concrete Structures Part 2 - Concrete Bridges”, Draf 8, 1994

F1 **Falcó X., Aparicio A. C., Barbat A. H., Rodellar J.**, "*Control activo de puentes sometidos a cargas de tráfico*", Centro Internacional de Métodos Numéricos en Ingeniería, Barcelona, 1990

F2 **FIP** - Handbook of Practical Design -” Example of the design of Concrete Structures”, Thomas Telford, 1990

F3 **FIP -** “Recommendations for the Design of Post-Tensioned Slabs and Foundation Rafts” (1995), Waiting Publication

M1 **Menn, C.,** “Prestressed Concrete Bridges”, Birkhauser Verlag,1986

O1 **Ontário Hightway Bridge Design Code,** 1983

P1 **Pacheco P.,** "*Nature´s Solutions for Structural Problems*", in Portuguese, M.SC. Thesis, F.E.U.P., Porto, 1993

P2 **Pacheco, P.** “*Aplying Effector Systems on Prestressed Bridge Decks*”, in Portuguese, PhD. Thesis, in preparation.

R1 **Radin E.R., Simon S. R., Rose R. M. , Paul R. M, Igor L.,** “Biomecânica - Prática em Ortopedia”, Editorial Limusa - Mexico, 1990

R2 **Regulamento para Estruturas de Betão Armado e Pré-esforçado,** Porto Editora, 1993

R4 **Rodellar J., Barbat A. H., Martin-Sanchez J. M.,** “Predictive Control of Structures”, Journal of Eng. Mech.s, ASCE, Vol. 113, Nº 6, pags. 797-813, 1987

R5 **Regulamento de Segurança e Acçôes par Estruturas de Edifícios e Pontes,** Porto Editora, 1993

S1 **Silva, Kello C.**, "Biomechanics research at the Gulbenkian Institute of Cience" in " Comunicações do tema nº6 do 1º Congresso Nacional de Mecânica Teórica e Aplicada", 1º Congresso Nacional de Mecânica Teórica e Aplicada, 1974

S2 **Soong T. T., Skinner G.,** "*Experimental study of active structural control*", Journal of Eng. Mech. Division, ASCE, Vol. 106, pags. 1057-1067, 1981

S3 **Sirkis J. S., Dasgupta A.**, “The Role of Local Interaction Mechanics in Fiber Optic Smart Structures” in “Recent Advances in Adaptative and Sensory Materials and Their Applications”, Technomic, 1992

T1 **Timoshenko S. P., Goodier J. N.,** “Theory of Elasticity”, International Student Edition, McGraw Hill, 1970

Y1 **Yang J. N., Giannopoulos F.,** "*Active tendon control of structures*", Journal of Eng. Mech. Div., ASCE, Vol. 104, Nº EM3, pags. 551-568,1978