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STRUCTURAL CONTROL TOWARD STRUCTURAL ROBUSTNESS

L. Faravelli[1] and S. Casciati[2]

[1] *Professor, Dept. of Structural Mechanic, University of Pavia, Pavia, Italy*
[2] *Assistant Professor, ASTRA Department, University of Catania at Siracusa, Siracusa, Italy*
Email: lucia@dipmec.unipv.it

ABSTRACT :

"Structural robustness" is a term recently adopted by the literature to frame all the scenarios the designer should add to those required by a mere (semi-probabilistic or probabilistic) safety analysis. These lifecycle scenarios can likely undergo unforeseen accidental situations. The consequences of some of them in terms of progressive collapse can be avoided just by a suitable conception of the structural system. If this is not the case, the structural components will be locally over-designed to avoid that the consequences of damages to structures be disproportionate to the causes of the damages.
Active, semi-active and hybrid structural control grew in the last two decades showing their ability to be designed and installed in civil engineering applications. Nevertheless, a strong safety requirement, demanding to provide the safety target even during the failure of non-passive components making a control policy uneconomical. This suggests to investigate different areas of exploitation, which can mainly be grouped in two classes: applications during the construction stage and implementation toward the achievement of a better structural robustness.
The latter aspect is discussed in this contribution with reference to two types of structures: suspension or cable-stayed bridges and monumental buildings.

KEYWORDS: Structural robustness, Progressive failure, Structural control, Suspension bridges, Monumental buildings

1. INTRODUCTION

The applications of structural control in Civil Engineering date back to the lecture held by Professor Kobori (Kobori, 1998) at the 9th World Conference on Earthquake Engineering, which sought the maturation of pioneering concepts (Yao, 1972).
After that, in the last twenty years, four world conferences on structural control (see the proceedings of the last one, (Johnson and Smyth, 2006)) were organized, new journals focused on the topic of structural control were started, a significant amount of papers have been published. The main issues approached by this research activity were of a technological nature, answering the question "how a predefined target can be pursued by exploiting the structural control potential". Not enough attention was paid to the "economical" aspects and to the "philosophical" need of inserting the new technology into a new operational framework: a) in a market ruled by prescriptive structural codes, there is not economical advantage to incorporate expensive mechanical and electronic components into the structural design; b) even in a performance-based design framework, safety issues must rely on the physical structure, without considering the further margin offered by the added intelligence. In other words, the owner of a building demanding innovative technology can see it implemented just to improve the system performance within the serviceability limit states and this will cost him/her all the additional expenses related with the control system equipment and its maintenance. As a result the few successful implementations of non-passive structural control must be recorded during the construction stages of skyscrapers and suspension bridges (Casciati 2008), i.e., applications of relatively short duration where the maintenance costs are actually null.
However, structural engineering research is going further the concept of safety and last years were characterized by the growth of the insight coming from a specific society demand, referred to as structural robustness. The concept is introduced in next Section, even if its theoretical modeling offers non-minor

difficulties. The further two Sections study the potential of structural control to ensure structural robustness for two specific classes of problems.

2. STRUCTURAL ROBUSTNESS

The lifecycle scenarios affecting a structural system may include rare, but possible extreme situations whose damaging consequences should be limited by a suitable conception of the structural system. This concept of structural robustness was clearly introduced by the Joint Committee on Structural Safety in its probabilistic model code (JCSS, 2001) and is the object of a topic Eurocode activity (prEN1991-1-7, 2004). Furthermore, it is becoming a stringent constraint within the performance based design and those national codes which are based on it (US General Service Administration and Applied Research, 2003). The main concern of related research is to conceive procedures which pursue the comparison of the robustness of structural systems, which, in a simplified form, can be pursued by robustness indexes (Baker et al., 2005).

Within this paper, a cost function is defined in the space of the design variables, and its value falls within an assigned range. Also a set of scenarios against which robustness should be assessed is introduced. The result will be a robustness index dependent on both the given range of design costs and the given aggression scenarios.

Following the approach suggested in (Rackwitz, 2002), the authors (Casciati, 2006 and Casciati and Faravelli, 2008) proposed to approach the decisional problem of the design of a public structure, whose reconstruction is systematic upon failure, as the minimization of the following objective function

$$F_C(\boldsymbol{x}) = C(\boldsymbol{x}) + [C(\boldsymbol{x}) + K]\left(\sum_{i=1}^{m} P_{f\,i}(\boldsymbol{x})\right) \Bigg/ \left(1 - \sum_{i=1}^{m} P_{f\,i}(\boldsymbol{x})\right) \tag{1}$$

where $\boldsymbol{x}$ is the vector which collects the design parameters; $C(\boldsymbol{x})$ is the design and construction cost of the structure, $K = K_H + K_M$ is the sum of the cost of saving human lives, K_H, and the direct cost of the structural failure, including both the damage and the debris removal, K_M. Finally, m is the number of failure modes and P_{fi} is the probability of the i-th failure mode. To ensure the functionality of the structure, the latter quantity must stay below a reference value, say $P_{f\,i} \leq 10^{-6}$ (reliability requirement).

In general, structural reliability is treated as a self-standing optimization problem, to be solved for any feasible solution of the optimization problem in (1). However, by adding to the cost function of Eq. (1) the reliability requirement, F_R, and the Kuhn and Tucker conditions, F_{KT}, it is possible to simultaneously solve both the reliability problem and the cost-benefit analysis, thus performing a one-level optimization (Rackwitz, 2002). Furthermore, indicating with F_I the robustness requirement identified for a specific structural system, it can also be included in the optimization problem by formulating a general objective function (Casciati, 2006) of the form

$$F(\boldsymbol{x}, \boldsymbol{u}_1, \ldots, \boldsymbol{u}_m) = w_C F_C(\boldsymbol{x}) + w_{KT} F_{KT}(\boldsymbol{x}, \boldsymbol{u}_1, \ldots, \boldsymbol{u}_m) + w_R F_R(\boldsymbol{x}) + w_I F_I(\boldsymbol{x}) \tag{2}$$

where

$$F_R(\boldsymbol{x}) = \sum_{i=1}^{m} \frac{10^{-6} - P_{fi}}{P_{fi}} \tag{3}$$

expresses the reliability requirement, while the term

$$F_{KT} = \sum_{i=1}^{m} \left[|\, g_i(\boldsymbol{u}_i, \boldsymbol{x})\,| + \sum_{j=1}^{N_j - 1} \left| \left(u_{ij} \left\| \nabla \boldsymbol{g}_i(\boldsymbol{x}) \right\| + \nabla g_{ij} \left\| \boldsymbol{u}_i(\boldsymbol{x}) \right\| \right) \right| \right] \tag{4}$$

accounts for the Kuhn and Tucker conditions, being $\boldsymbol{u_i}$ the variables resulting from the transformation of the original random variables in the standard normal space (in number of N), and $g_i(\boldsymbol{u}_i,\boldsymbol{x})$ the i-th limit state function, with $i = 1, ..., m$. When, for any i, both the contributions to F_{KT} are null, $\|\boldsymbol{u}_i\|$ represents the value of the reliability index β_i for the i-th failure mode, from which one determines P_{fi} as: $\Phi(-\beta_i) = \Phi(-\mu_{gi}/\sigma_{gi})$. As usual, $\Phi(.)$ indicates the standard normal cumulative distribution function. Each term of the sum in the r.h.s. of Eq.(2) is multiplied by an adequate weight (or Lagrange multiplier), w_X, whose value depends on the safety margin within which the associated requirement must be fulfilled.

The robustness term in Eq. (2) is given the form of an index (Casciati and Faravelli, 2008). It is strictly associated to the nature of the numerical example. It mainly promotes the failure modes causing sustainable losses respect to those occurring with heavy losses:

$$F_I = 1 - \frac{P_{f_a} + P_{f_b} + \cdots}{\sum_i P_{f_i}} \tag{7}$$

where the denominator in the l.h.s. is the sum of all the probabilities of failure while the numerator does not account for the sustainable failure mode. It is likely that the presence of the robustness term in Eq. (2) will increase the cost of the design. The next two Sections explore the possibility of transferring to structural control the additional robustness demand.

3. TENSIONED CABLES

Steel cables are a core structural component in cable-stayed and suspension bridges. Long cables, however, are often prone to large amplitudes of vibration which usually ensue from a loss of dynamic equilibrium stability such as in the case of galloping and wind-rain induced oscillations. As it is well-known, these undesired levels of vibrations may lead to fatigue cable or connection failures as well as produce discomfort and runability problems.

With reference to Figure 1, where both the main cables and the hangers of a suspension bridges are visible, the problem of cable vibration mitigation via structural control policies attracted a great attention from the scientific community leading to a rich technical literature (Casciati et al., 2008; Casciati and Ubertini, 2008). Within this field, either passive or active solutions were extensively explored. Passive solutions are mainly based on transversal actuation by mounting dampers transversally to the cable. However, the localisation of the dampers, close to the cable support, generally limits the maximum achievable damping and this is especially true for long cables. A way to dramatically increase the damping introduced in the system is to replace the dampers by suitable active or semi-active actuators.

The idea illustrated in (Faravelli et al., 2008) is to match together the distributed passive solution utilizing wrapped SMA wires and a semi-active open loop control strategy which does not require state estimation and thus matches the requirement of a large control robustness. This semi-active strategy is based on nonlinear energy transfer between modes which take place in the nonlinear regime due to modal couplings. By operating in the above described way one obtains a hybrid intelligent control policy for cable vibration mitigation which is adaptive in the sense that it exploits the semi-active external control input only when necessary. Test was carried out on the physical cable model, of span length L=2.36 m, of Figure 2

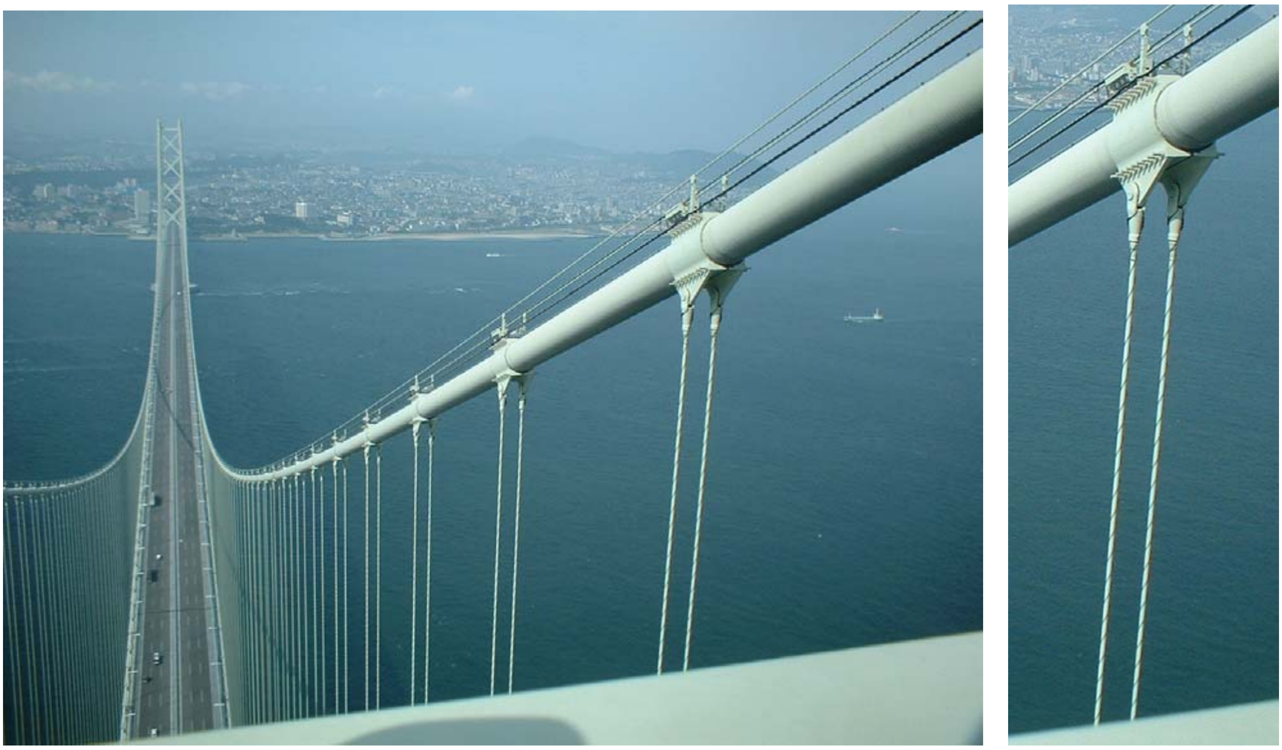


Figure 1 The Akashi suspension bridge: cables and hangers and detail of the hanger with the spiral intended to reduce the acoustic noise.

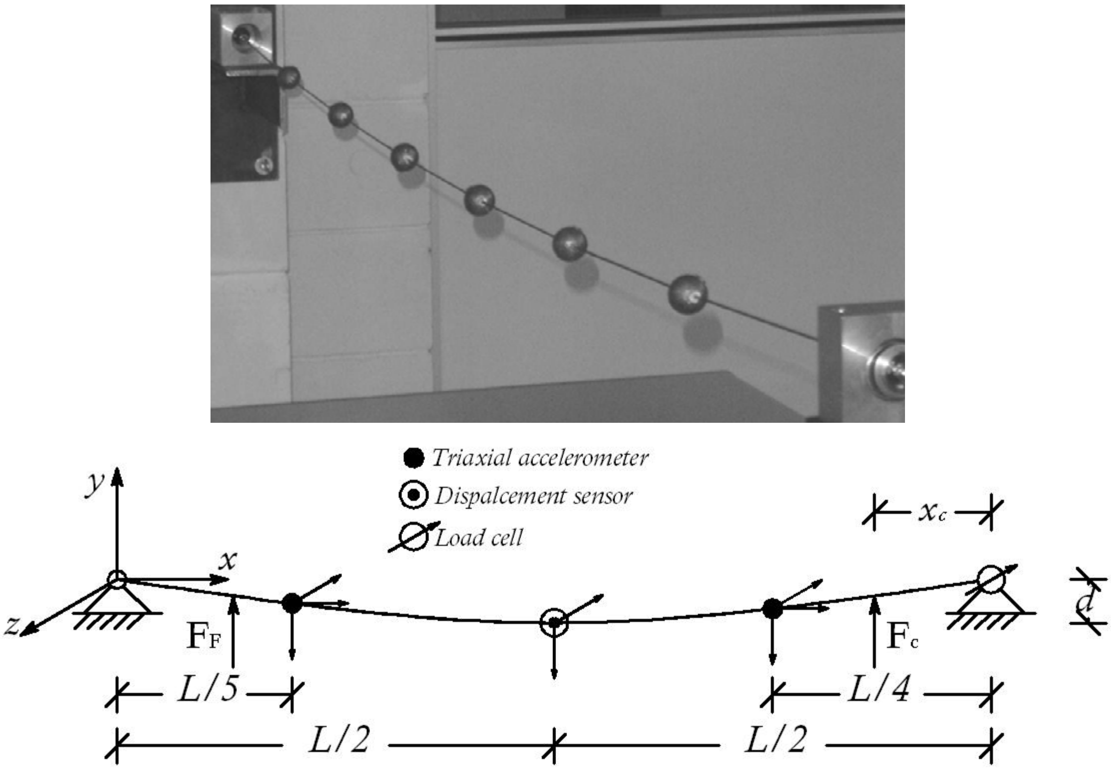


Fig. 2 Experimental setup and control architecture

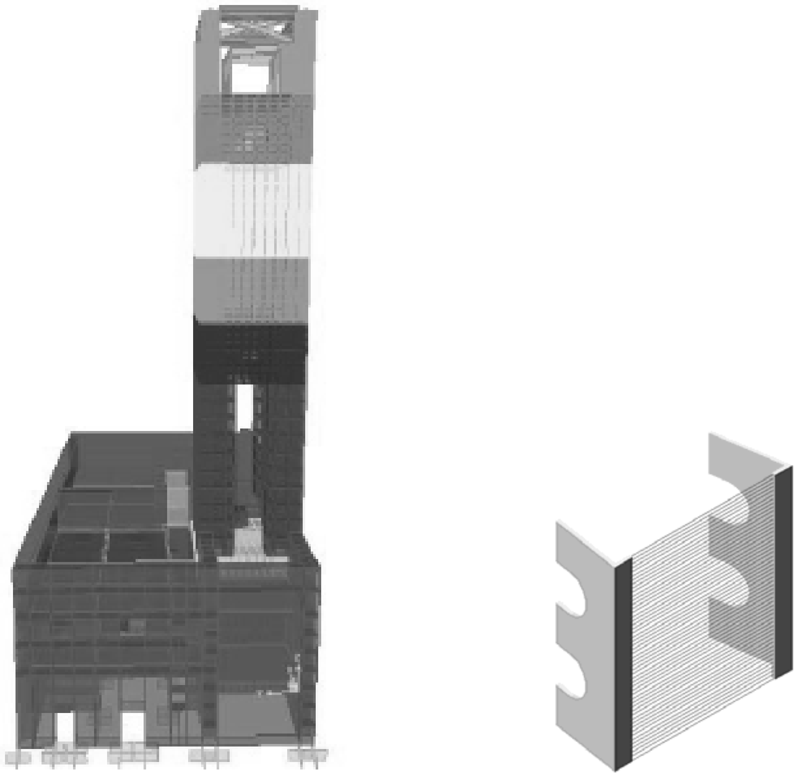
The anchorages are realized by inserting the end threaded parts of the cable in the spherical joints. Two laser sensors, type Wenglor, allow to measure the vertical movements v_0 in the in-plane direction (parallel to axis y) and w_0 in the out-of-plane one (parallel to axis z), of a point placed in the middle of the cable span L. Two tri-axial accelerometers, Crossbow LF type, are fixed to the cable approximately to the three quarters of the span and to the one fifth of the span, respectively. The accelerometers record the acceleration time history signals both in the vertical in-plane, $\ddot{v}_1$, $\ddot{v}_2$, and in the transversal out-of-plane directions, $\ddot{w}_1$, $\ddot{w}_2$, of the two application points.
In the proposed semi-active policy, a transversal vertical control actuator, represented by a linear motor, is placed in the vicinity of one of the cable ends (at a distance x_c) and exerts a suitable control force F_c (see Fig.2). The aim is to mitigate the cable response in the strongly nonlinear regime, i.e. when it is characterized by large limit cycles. Namely, the control force has the purpose of destroying the limit cycles by transferring the energy to high order modes and to drive the motion towards alternative dynamic regimes characterized by lower vibration amplitudes. The control strategy exploits the nonlinear couplings between modes in order to make the vibration energy flow from low order modes (namely the first in-plane mode) to higher order ones. Indeed, if one succeeds in increasing the frequency of the motion via some nonlinear energy transfer mechanism, a reduction of the transversal displacements of the cable is likely expectable.

The second approach for mitigating the cable response is to increase the modal damping of the structural system by wrapping a shape memory alloy (SMA) wire along the cable. A campaign of experimental tests was carried out toward the identification of a strategy capable to reduce in-plane and out-of-plane vibrations of cables and to increase their modal damping ratios. The idea is to create a composite system by coupling a steel taut cable and a thin SMA (copper-based) wire. Adding a pre-stressed shape memory alloy wire to a steel taut cable provides a mitigation solution distributed along the cable and, hence, it is not affected by the device localisation. The wire in shape memory alloy (austenite phase) of diameter 1mm is anchored to the same vertical point of the steel cable, and it is fixed at each end by a device that allows to assign a pre-tension force to the wire. Initially its value is selected to give a 2% strain in the cable. In the forced vibrations the pre-tension force is changed in such a way to measure a value of SMA wire strain between the 1% and the 3%. Semiactive solutions can be adopted to vary the tension in the wires when required.

As said in the introduction, the purpose of such a control strategy cannot be to assemble elements of reduced size and/or resistance because the extreme response to extreme hazard is prevented by the control devices. These long span bridges are designed with impressive expected lifetimes of 150 or 200 years, which obliges the designers to enter the area of progressive failure. Provided that a hanger fails, the bridge, even if no longer operative, must survive long enough until the undamaged state is recovered. To obtain this the hangers should be either over-designed or assisted by a suitable vibration mitigation scheme. The control system, therefore, will have two functions: during the standard operation stages it contributes to the full satisfaction of the serviceability limit states, but its value is better appreciated in the extreme situations. Here the control system will prevent from any negative evolution of possible progressive failure paths.

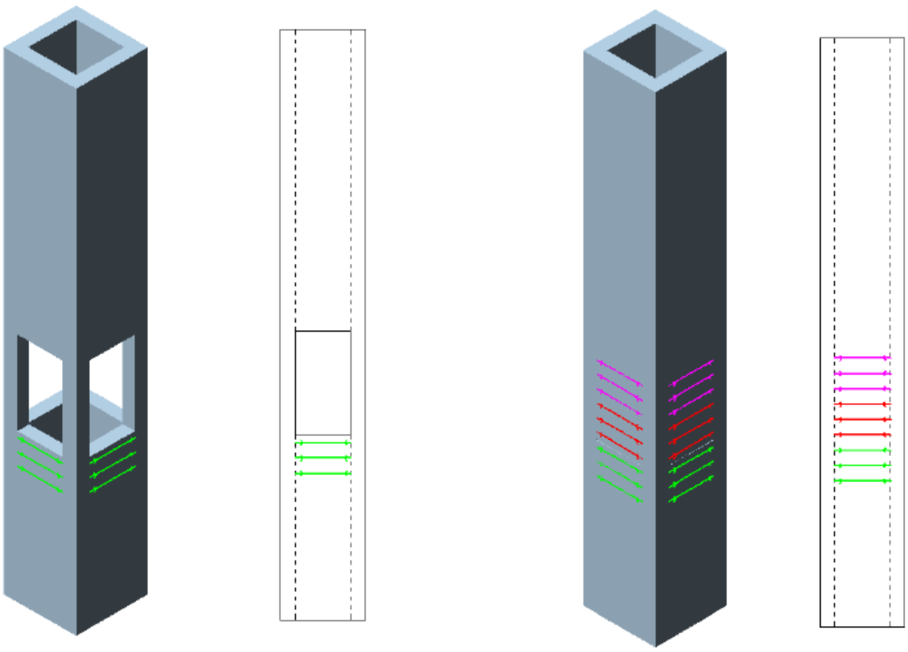
4. MONUMENTAL BUILDINGS

At the beginning of the twentieth century, the failure of the San Marco bell-tower in Venice represented a general warning of the durability of these slender masonry structures, which are characteristic of many urban nuclei in the Mediterranean basin (Sepe et al., 2008). Similar studies were also conducted in Islamic areas to preserve mosque minarets (El Attar et al., 2008). Within all these works, three stages can usually be distinguished: monitoring, diagnostics, and retrofitting.
The authors were responsible for organizing the instrumental monitoring of the civic tower of the small town of Soncino, located in the Northern Italian region named Lombardia. The recorded signals were used to localize the damage with structural effects (diagnostics), as different from cracks which only represent architectonic damage. The resulting damaged finite element model is given in Figure 3a).



a) b)

Fig. 3 a) Finite element model of the tower in the existing state; b) The retrofitting device in SMA wires, to be mounted on the internal part of the walls.



(a) (b)

Figure 4 - Different extensions of the retrofitting: a) bottom part only; b) full sewed.

Once the damage has been localized, the next step is to investigate the possible retrofitting solutions. Following the strategy proposed in (Casciati and Hamdaoui, 2008). The retrofitting is pursued by adding ties made of pre-tensioned shape memory alloy wires. They are mounted using the device shown in Figure 3b), with the two steel oblique plates placed across the entire wall thickness. This device can be mounted inside the tower and, as such, it has the advantage of not being invasive. Furthermore, this type of intervention also offers the advantage of reversibility, since it can be removed without leaving any permanent effect on the structure. If necessary, any semiactive control policy can be adopted to update the tension in the wires.

This retrofitting stage is approached in (Faravelli and Casciati, 2008) by numerically investigating the effects of different solutions. Indeed, different spatial distributions of the retrofitting devices can be conceived (two among them are represented in Figure 4). The design choices are driven by comparing the simplified vulnerability curves associated to several spatial distributions of the retrofitting devices along the tower height.

Once again, monitoring the retrofitted solution to give a feedback to a semiactive control of the tension in the wires does not find its main justification in safety arguments, because in this way the ties prevent from the fall of masonry blocks and because the device itself is able to retard the progressive failure of the tower under extreme external events.

5. CONCLUSIONS

Structural robustness is intended to prevent extreme consequences, such as the progressive collapse of a structure, following unforeseen accidental actions. This paper works in the framework which sees structural robustness directly accounted in a reliability-oriented optimal design, where one simultaneously pursues the minimization of the cost and an adequate structural performance. The latter one should now be evaluated in terms of both reliability and robustness. For this purpose, an index which quantifies the concept of robustness is formulated. Nevertheless, while reliability requirements “de facto” determine the cost, robustness should be pursued within a range of affordable extra-costs. The idea of assigning this task to structural control is investigated. The specific cases of bridge cables and of monumental masonry are discussed in some detail.

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