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An actively controlled prototype for educational buildings

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Abstract. The authors address the problem of ameliorating or updating existing educational buildings. This building typology is quite sensitive to social and media pressure, mainly when accidents have occurred nearby. When a building is classified as unsatisfactory, the current code requirements oblige one to re-design the building with significant penalty factors in the resistance values. Often the only solution is to destroy the existing facility and to build a new one. When attempting to preserve the existing building, higher levels of safety are demanded by the society and this can only be achieved by innovative system architectures. The authors propose and discuss a prototype that can be easily adopted to retrofit small educational buildings as the ones common in small municipalities. The higher performance is pursued by a special design of the control scheme, with new control devices and special control laws.

Keywords: active control; building amelioration; braking control; educational buildings; structural control paradigm

1. Introduction

Buildings that host either hospitals or educational systems always require, as any other residential construction, continuous maintenance (Erhorn-Kluttig *et al*. 2016). However, due to their central social role, they also undergo periodically the need for a deep structural updating. This is mainly a consequence of structural degradation (Casciati and Faravelli 1991), but the updating must also be tuned with the periodic update of the construction technical codes. A serious modification, for instance, could be the assignment of the building location to a higher demanding seismic zone. One distinguishes two possibilities: amelioration and retrofitting. The first intervention aims at increasing the building structural safety without a full satisfaction of the requirements of the updated code, while the second word denotes a full structural rearrangement consistent with the updated structural code.

An EU INTAS (European Union, International Association for the promotion of cooperation with scientists from the independent states of the former Soviet Union) research project, dating back more than a decade ago, jointly afforded the problem (Syrmakezis *et al*. 2006). In the meantime, the literature reports significant progresses for hospitals (Myrtle *et al*. 2005, Tesfamariam and Wang 2012), while dealing with educational buildings showed more difficulties due to their quite broad diversification in terms of structural type, architectural features and age (Shrestha *et al*. 2008, 2009). Nevertheless, a general study is available (Smyth *et al*. 2004) as well as applications (Hancilar *et al*. 2014).

This contribution introduces the topic and focuses on the consolidated steps along the technical process. The core is the availability of the information: bits of information on the structural skeleton geometry and on the material mechanical properties play a dominant role on the chance of making the retrofitting feasible or not. Indeed, present structural codes impose significant penalty factors to the design parameters when the designer is operating in a situation of lack of information.

The authors discussed the problem of ameliorating and retrofitting educational buildings in (Casciati and Casciati 2018, Casciati 2018). A few items that could significantly improve the whole process of amelioration or retrofitting are given below:

(a) To require the extraction of the environment-induced building-frequencies would help in the calibration of its numerical model and, hence, in the accuracy of the estimated response;
(b) To accept that the amelioration is designed in derogation of the national code for existing buildings would help to catch the actual seismic weakness in the system architecture, rather than to cover weaknesses arising from lack of information;
(c) To allow a performance based approach (today illegal in Italy, the country of the authors) would emphasize the weights of the designer choices when he/she want to select adequate, targeted safety margins.

After a short synthesis of the proposed technical steps, the authors focus attention on a specific aspect of structural control, which often represents the only way to make the amelioration feasible.

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2. A collection of case studies

The first information source relies on the technical archives, richer and richer as younger the buildings are. Any structural system has then to be visually inspected. Specialty teams, able to assess the geometry of the structural elements and the type and quality of the materials by non-destructive testing, can be employed. A valid option is to install in the building devices (accelerometers) able to catch the structural system signature.

It must be outlined that three main difficulties are met in the estimation of the seismic vulnerability of educational buildings:

(1) To understand the foundation system; in some areas the foundation soil often requires the collaboration of micro-piles, whose tracks are difficult to be detected. Sometimes there are cracks all around the walls and they are suspected to be originated by foundation settlements.
(2) To understand the roof system; its upside is often accessible by an external access while the skeleton of the supporting structure can only be hypothesized.
(3) To model the basement; the actual interaction between the soil and the basement wall can only be assumed, never being detectable with evidence.

A further source of complication covers those building made by the ground floor only, or by ground floor and basement. In these cases, the stair wall is absent and attention must be paid to the way by which the horizontal forces are transferred to the vertical skeleton. Only in rare cases, one can detect the presence and nature of braces.

All the collected bits of information have to be incorporated in a numerical model and four main steps follow:

(a) Validation of the numerical model by static analyses under permanent loads. No safety factor is considered;
(b) Assessment of the safety margins for all the actions in combination except the seismic excitation;
(c) Considering the seismic load combination with the peak acceleration increased by a factor from 0 to 1. In this way the current structural vulnerability of the system is assessed.
(d) If necessary, adequate retrofitting solution are incorporated.

Fig. 1 provides some examples of analyzed case studies in North-Western Italy.

A first code trap is met when discussing the mass to be added when the accidental vertical load is considered. The code (i.e., the coercive law in Italy), says that the designer has to introduce a factor lower than one, which alters the modal frequencies of the building. Even if the designer has evidence of a more significant and non-homogeneous distribution of these masses, there is no way to be coherent with this precious bit of information. It is worth noticing that an easy way to achieve element retrofitting is to add fibre reinforced mortars, i.e., masses that can result quite negative when the dynamic shake is considered


(a) Secindary SHOULD BE Secondary


(b) Professional school in Borgonovo Val Tidone


(c) Kindergarten in Pavia


(d) Secondary school in Castelnuovo Scrivia


(e) Primary school in Pavia


(f) Primary school in Dovera


(g) Kindergarten in Fossarmato


(h) High school in Pavia

Fig. 1 Examples of reinforced concrete educational buildings in North-western Italy

The second, and quite more significant, code trap is met when introducing the safety factors, which have to be penalized by a factor 1.20 or 1.35 according to the level of information: poor and lacking, respectively. This is because of the code obligation to retrofit the building when updating its seismic strength. The frequent lack of information on the actual description of the structural system obliges the designer to assume reduction coefficients for the resistances. The consequence is that several structural elements are inadequate even under the action of dead load and accidental vertical load.

Tables 1 and 2 provides a synthesis of the beta safety indexes (Casciati and Faravelli 1991) for a significant couple of beam and column in the height educational buildings in Fig. 1, when only static gravitational loads are considered. The couples considered for Table 1 are not those considered for Table 2, but their internal actions are similar. The main difference is that the coefficient of variation of the random design variables are set to a high value in Table 1 and to a low value in Table 2.

It is seen that lower values of the coefficients of variation of the design variables come with larger values of the safety index (with just an exception in italic in Table 2: this specific result is due to the quite different working regime in the two studied cases).

Table 1 Estimated values for the safety index beta when the coefficients of variation of the random variables (namely, Young modulus, geometry, life load and strength) are set to high levels among the likely ones

Fig. 1	Beam	Column
(a)	3.2665	3.1161
(b)	4.2380	4.4886
(c)	3.4288	3.9874
(d)	3.6857	3.6776
(e)	3.5512	2.6862
(f)	3.7263	3.4815
(g)	4.0168	3.9939
(h)	3.3782	3.5239

Table 2 Estimated values for the safety index beta when the coefficients of variation of the random variables (namely, Young modulus, geometry, life load and strength) are set to low levels among the likely ones

Fig. 1	Beam	Column
(a)	3.8998	3.5555
(b)	4.9411	5.3285
(c)	3.4831	5.5682
(d)	6.1864	4.0448
(e)	5.2914	4.3696
(f)	6.6204	4.9436
(g)	6.0425	*2.9314*
(h)	6.0629	6.3342

When the seismic action is added the values in the two table are generally decreased. Provided the reduction is below the 15%, one could conclude that no amelioration or retrofitting is required.

By contrast, higher reductions of the safety indexes would require the design of an improved solution. It is here that the penalty factors on the resistance values apply and the feasibility of any upgrade could become hard. Passive control solutions are usually scanned. In this section an active control scheme which could be applied to small educational buildings as those in small villages and municipalities is proposed.

3. A structural control approach

(Casciati *et al*. 2014) is mainly dedicated to the discussion of a paradigm for structural control, if any. Actually one reads:

"The term "paradigm" was coined to characterize the set of agreed positions upon which the consensus is based. These agreed upon positions are the results which form the handbook of a discipline, where the rules of approach are identified through the consensus of the scientific community. This consensus comes either from verification or from falsification.

For the field of structural control in particular, the associated disciplinary "paradigm" has not been completely characterized yet…"

Three items are worth being mentioned:

(1) The crucial question for any scientific discipline (Fornero 2006), including the discipline of structural control, is: What is the ultimate goal?
(2) With focus on the field of civil engineering, the following specification applies: "the structural control strategy is targeted at counteracting impact of random excitations, such as earthquakes, wind, explosions, etc., while the most important problem of vibration mitigation in mechanical engineering consists in counteracting periodic or poly-harmonic excitations" (see (Kolovsky 1999), among others).
(3) Structural control in mechanical and aerospace engineering is a discipline using the same conceptual tools, but civil engineering applications are commonly characterized by large masses, long lifetimes, and the need for adequate safety and robustness.

Looking for a breakthrough, out from a standard building architecture, two different active control schemes, both relying on motion along rails, are conceived and illustrated. Then a numerical model of the second scheme investigates their feasibility.

The question in item 1) is answered by addressing the design effort to serviceability limit states by demanding extreme events to a parallel strategy. By the way, in a step-by-step analyses, to preserve serviceability limit states infers that the structure works far from any ultimate limit state. Of course, safety is also guaranteed for short duration extreme conditions; otherwise, the system response can be driven far away from the controllable region.

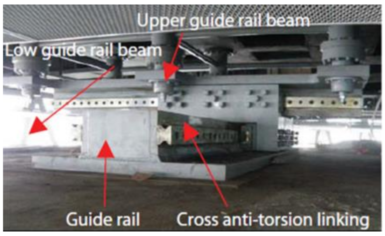

Fig. 2 Bidirectional rail scheme as taken from the literature

A different structural architecture is coupled to standard numerical modelling to meet the needs of specific tools against specific actions (item 2). In particular:

(A) A rail bidirectional system is studied for active control of educational buildings under the seismic action. Due to their high societal value, the public opinion is ready to afford significant investments to preserve scholars' integrity.
(B) A rail circle is interposed between the foundation soil and the building, as sustained by a rather stiff supporting plate.

By numerical modelling in a suitable commercial software, the feasibility of the studied design solutions can be stated.

Actually, the first scheme can be easily found in the literature at small and large (see Fig. 2) scale. The main inconvenience comes from the need to have a large surrounding area free of obstacles so that the building can move along the rails as driven by the incoming event of environment excitation.

The carousel like solution of Fig. 3 does not suffer of this inconvenience. In particular, Fig. 3 provides the initial position of the rails (un-deformed shape) together with the situation one observes when the foundation soil is moved up in the horizontal plane. Numerical results say that the displacement of the supported building is just one half of the values imposed at the foundation, even for assigned initial friction.

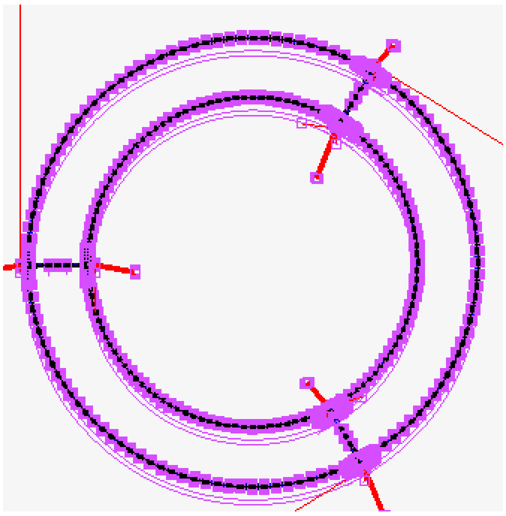

Fig. 3 Response of the mechanical system to a translation of the foundation soil

The active control features are:

(i) The active system serve as a brake, but the trade-off "at-rest versus motion" results in accepting some motion;
(ii) The control law of brake systems are well known in the literature. But some potential drawbacks should be afforded case by case.

4. Conclusions

The authors outline the social interest of procedures for ameliorating and retrofitting educational buildings, procedure that find serious obstacles in the current structural regulations for existing buildings. These rules strongly penalize situations where there is not full information on the initial design scheme. Consequently, any intervention is likely to result either in significant addition of structural material or even into a final evidence of unfeasibility.

Moving from the remark that a simple coupling of structural design with control design could result ineffective, the author discuss the potential of simple integrated designs from the mechanical point of view.

Abandoning standard building topology results in a list of consequent drawbacks that have to be approached and afforded one by one.

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