Integration of Seismic Risk into Energy Retrofit Optimization Procedures: A Possible Approach Based on Life Cycle Evaluation

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Abstract. Most of the retrofit processes applied to existing buildings are frequently targeted at reducing energy consumption over the building lifetime, neglecting possible interactions with other sources of uncertainty. On the contrary, recent Italian earthquakes highlighted the need to couple energy aspects with structural retrofit design to avoid tragic consequences and optimize, at the same time, the rational use of environmental and economic resources. The interaction between the two aspects has been rarely managed following design codes due to the absence of methodological frameworks. Motivated by these considerations, the study aims to integrate energy and structural aspects related to seismic risk in a life cycle-based decision-making framework for the retrofit design of existing buildings. As a case study, the methodology is applied to a three-storey RC building assumed to be located in different Italian sites. These are characterized by different climatic conditions and seismicity levels.

1. Introduction

Most of the European buildings built before 80ies were conceived without any design concerns for energy efficiency or seismic provision in case of earthquake prone areas; in addition, the awareness about environmental sustainability was not yet developed as the way it is today. In Italy, the first national measures for improving the energy efficiency and seismic performance of new buildings date back to 70ies, when important national rules were promulgated:

• 1976 and 1977: introduction of national guidelines for improving energy efficiency of new buildings (Italian Law 373/76 [1], Italian Decree D.M. 10/3/1977 [2], and Italian Decree D.P.R. n. 1052 28/06/1977 [3]);
• 1974: implementation of specific measures for seismic risk mitigation on new structures (Italian Law 64/74 [4]).

The statistical analysis of the year of construction of Italian existing buildings inevitably returns an “unsustainable” situation with respect to the above-mentioned dates [5]. Indeed, approximately 60% of the Italian existing building stock is severely lacking regarding design concerns for energy efficiency or anti-seismic building specifications. This context certainly entails an issue of sustainability that has
to be tackled in light of the goals foreseen by 2030 Agenda for Sustainable Development (in particular, Goal 11: “Make cities and human settlements inclusive, safe, resilient and sustainable”).

Possible strategies to foster sustainability of the existing building stock include demolition and reconstruction or refurbishment/retrofit; the latter is significantly important especially when an historical value is associated to the target building. However, over the last decade, due to the low rate of new constructions, the attention of engineers and practitioners has been mainly focused on the refurbishment/retrofit. Generally, the design framework for refurbishment/retrofit interventions is intended to pursue a set of objectives, indicators or performance criteria belonging to the key objectives of sustainable development; these are commonly represented in terms of a triple bottom-line strategy [6], i.e. through the simultaneous fulfilment of environmental, economic and social goals. However, many of the studies or practical cases dealing with large-scale retrofit have focused on single aspects, such as energy or structural performance of retrofitted structures[7]-[11], while few works have dealt with the integration of different sustainability objectives [12]-[15]. On the other hand, multi-disciplinary approaches capable of maximizing the benefits of integrated retrofit strategies (i.e., encompassing the simultaneous consideration of energy, structural and environmental aspects) would be fundamental in Italy [17, 18] where the territory and existing buildings are characterized by: (i) high vulnerability; (ii) large areas prone to seismic risk (approximately 44% of the Italian surface) where 5.5 million historic value buildings are present (involving approximately 36% of the Italian population); (iii) wide range of climatic zones with variable and significant values of energy demands for space heating and cooling.

A comprehensive representation of this complex situation can be provided by the combination of two main site-dependent input parameters (Figure 1a and 1b) that, with a view of an integrated energy-structural retrofit approach, should be evaluated before the retrofit design itself. The input parameters aim to describe the climatic zone and seismicity of the building locations by means of, respectively: (i) the Heating Degree Days index, (HDD, which is referred to the heating season) defined as the cumulated of all the positive differences between the daily mean outside temperature and an internal set point temperature equal to 20 °C, during the whole heating period; and (ii) the peak ground acceleration (PGA) expected with a 10% exceedance probability in 50 years (return period of 475 years).

The spatial distribution of the two site-dependent input parameters highlights that many Italian areas (e.g. central Italy, north east Italy etc.) are simultaneously prone to earthquakes and high energy demands for space heating. Consequently, independent retrofit strategies aimed, for instance, to reduce energy consumption would probably generate a waste of money or environmental resources if the
A retrofitted building is not able to properly resist a very likely seismic event (e.g., see [14] where the authors have demonstrated that the energy payback time of retrofit interventions can even double for very seismic-prone areas).

The methodology herein presented aims to integrate energy, environmental and overall cost sustainability objectives in a life cycle perspective and is referred to existing reinforced concrete (RC) buildings. The study represents a first step towards the integration of seismic risk into energy retrofit optimization procedures based on Life cycle evaluation and can be further extended to existing masonry structures. As a case study, the methodology is applied to a three-storey RC building assumed to be located in different Italian locations characterized by different climate conditions and seismicity.

2. Methodological framework for combined energy-structural retrofit

The proposed methodology framework integrates the seismic risk assessment into an optimization procedure to address building energy retrofit over a building life cycle perspective. The final aim is to achieve a cost-optimal combined with energy-structural retrofit of existing buildings. In detail, a wide domain of energy retrofit scenarios (starting from a set of energy retrofit measures, ERMs) is firstly considered and numerically treated in order to identify the cost-optimal solution for a given structure. Afterwards, the influence of the cost-optimal energy retrofit solutions on the expected economic losses due to seismic events is assessed. Once the ERMs are implemented into a cost-model associated with the building structure performance, the final step consists in the assessment of the cost-effective strengthening strategy that ensures a pre-defined strengthening level (i.e. associated with a given safety level) over the building. The outcome of this methodology is the most cost-effective life-cycle-based retrofit solution that is able to minimize the total lifecycle cost (LCC) due to investment, energy running costs and structural/non-structural losses over the building (new) lifetime, including different sources of uncertainty (e.g., the occurrence of hazardous event such as earthquakes). In other words, the implementation of the methodology turns back the optimal set of energy and structural retrofit measures that are able minimize the total life cycle cost, which includes investments, running costs for energy services and seismic economic losses, during building lifetime. Consequently, the methodology can represent a reliable support for the decision-making stage of integrated retrofit strategies. It should be also pointed out that also other sustainability aspects can be included in the analysis (e.g., environmental burdens) but they are not included in this study for sake of brevity.

The methodology can be implemented through different analytical steps and aims to quantify and minimize the overall economic life cycle cost (LCC) associated with combined energy and structural retrofit of an existing building. In particular, the energy performance evaluation refers to a set of ERMs applied to the existing building whereas the structural performance is considered in order to quantify the economic losses due to seismic induced damage (see Figure 2). LCC is assessed by summing up the global cost (GC) for energy issues and the expected annual losses (EAL) due to seismic hazard – properly discounted – over building lifetime. In this regard, GC takes account of investments for ERMs as well as of discounted running costs for energy services over building lifecycle. GC is assessed according to the EU (European Union) Guidelines [19, 20] by using equation (1):

\[
GC(\tau) = \sum_j \left[ \sum_i (RC(i) \times D_R(i) - V_{f,\tau}(j)) \right] + IC
\]

where:
- \(j\) is an index that denotes the ERMs;
- \(i\) is an index that denotes the year;
- \(\tau\) is the considered time horizon, set equal to 30 years for residential buildings and 20 years for non-residential ones [19, 20];
- \(RC(i)\) is the annual running cost for energy needs;
- \(D_R\) is the actualization factor; in this regard, the discount rate is set equal to 3% [19, 20];
- \(V_{f,\tau}\) is residual value of the investments at the end of the evaluation period;
- \(IC\) is the total investment cost for ERMs and strengthening measures (if these are implemented).
On the other hand, the expected annual losses (EALs) due to the occurrence of earthquakes are assessed according to the procedure taken from [21] and expressed by equation (2) in terms of total losses over the selected time interval \( \tau \):

\[
EAL(\tau) = D_R \times \sum \left[ C(i) \times \lambda(i) \right] \tau \tag{2}
\]

where:

- \( EAL(\tau) \) is the total loss computed over the selected time interval \( \tau \);
- \( C \) is the replacement or restoration cost of the building after a seismic event in the year \( i \) (i.e. the expected loss);
- \( \lambda \) is the probability of occurrence of a seismic event in the year \( i \);
- \( C(i) \times \lambda(i) \) is the EAL in the year \( i \).

Finally, the total life cycle cost is assessed according to equation (3):

\[
LCC = GC(\tau) + EAL(\tau) \tag{3}
\]

Figure 2. Schematization of structural-energy interactions in terms of life cycle economic costs

According to the proposed methodology, the building energy-structural retrofit optimization consists in the minimization of the overall \( LCC \), following four main steps:

- **Step (1)** — Optimization of building energy retrofit from a wide set of possible and compatible packages of ERMs, using the optimization procedure based on a cost-optimal approach proposed by the authors in [14]; this procedure implements a multi-stage genetic algorithm (stage I) and a smart sampling of retrofit solutions (stage II).
- **Step (2)** — Assessment of seismic economic losses for the “as built” existing building throughout its lifetime by the quantifying seismic induced damages and the related economic investment to restore the damaged components.
- **Step (3)** — Integration of energy and structural aspects by linking cost optimal ERMs (concerning the building envelope and overall systems) to the level of seismic induced damage of the non-structural components (using proper engineering demand parameters [16] and component performances).
- **Step (4)** — Assessment of the influence of optimal ERMs on seismic economic losses by quantifying the difference in global \( LCC \) (i.e. from eqn. (3) in terms of updated savings and payback time) with respect to the as built configuration.
Step (5) — Determination of cost-effective structural retrofit solutions based on a set of possible techniques and achievable safety levels; in this step upgraded seismic economic losses (i.e. including cost optimal ERMs) are minimized throughout the (new) building lifetime. Finally, the cost-optimal solution, which minimizes $LCC$, is provided for the energy-structural retrofit of the building.

The outcomes of this methodology can be useful for the selection of proper ERMs and strengthening strategies, looking at the overall cost-effectiveness (or, more in general, other sustainability parameters) of the retrofit itself throughout the building life cycle.

3. Case study
A reinforced concrete (RC) structure has been assumed as case study for implementing the methodology described above. The building is a typical example of an Italian facility built in the 1970s according to the old building code and without any seismic or energy prevision (Figure 3). The floor plan has an approximate rectangular shape and dimensions of $48.1 \times 18.1$ m, with a total area of about $870 \text{ m}^2$. The total height of the building is $10.1$ m and it consists of three floors with a storey height of $3.2$ m, except for the first floor, which is $3.7$ m. The structure is composed by RC frames in two directions. The foundation system is composed of RC footings and connection beams framed in two orthogonal directions. Each story hosts five apartments. The building envelope presents low thermal resistance, like large part of Italian existing buildings (built before the 1980ies). In this regard, the vertical external walls are made of hollow bricks and have thermal transmittance (i.e., U-value) equal to $1.23 \text{ W/m}^2\text{K}$. The horizontal envelope is made of mixed brick-reinforced concrete and the U-value is equal to $1.05 \text{ W/m}^2\text{K}$ for the roof and to $0.90 \text{ W/m}^2\text{K}$ for the basement floor. Finally, the windows are double-glazed with wooden frames and have U-value equal to $2.67 \text{ W/m}^2\text{K}$ as well as solar heat gain coefficient (SHGC) equal to 0.691.

The building is assumed to be located in three different Italian cities, namely Benevento, Lattarico and Spoleto. These are characterized by different climatic conditions, but they are exposed to a similar level of seismic risk. Indeed, the PGA (peak ground acceleration) demand values are $0.251g$ for Benevento, $0.260g$ for Lattarico and $0.221g$ for Spoleto, considering as seismic demand a severe earthquake with a return period of 475 years, according to the Italian National Building Code. As concerns the climatic scenario in terms of HDD (heating degree days), Benevento, Lattarico and Spoleto belong to the Italian climatic zone C, D and E, respectively (according to the map of Figure 1a).

Steps (1), (2) and (3) of the proposed methodology for the case study were completed following the approach presented by the authors in [14] and not reported here for sake of brevity. Then, in order to estimate the most cost-effective structural retrofit solution, the costs of each strengthening technique along with the related building seismic economic losses at different intensities of the retrofit interventions were computed.

In this case study, retrofit strategies aiming at increasing ductility, stiffness, and strength, or all of them, were selected. In particular, the following retrofit strategies were investigated:

1. Use of RC shear wall-based strengthening systems (i.e. insertion of shear walls to sustain the seismic action in both the longitudinal and transverse directions).
2. RC jacketing-based strengthening solution (i.e. RC jacketing of beams and columns to increase the flexural and shear capacity of members, as well as ductility, and to increase the global structural stiffness).
3. Fiber-Reinforced Polymer, FRP – RC jacketing-based strengthening solution (i.e. a combined strengthening solution based on the previous solution and the shear strengthening of beam-column joints and beams using FRP sheets to prevent brittle failure mechanisms).

The achievement of a failure mechanism identifies the PGA capacity of the retrofitted structure and corresponds to the hazard intensity that would induce the structural failure. The ratio between the PGA capacity and the PGA demand defines the safety level.
4. Results and Discussion

The results are reported in terms of reduction/saving of the total life cycle cost, \( LCC_{\text{sav}} = LCC_B - LCC_{\text{LCCsav}} \), i.e. obtained by comparing the as built as-built and retrofitted configuration life cycle performances (denoted with the subscript \( B \)). When \( LCC_{\text{sav}} \) is positive, the proposed energy-structural retrofit provides a saving of overall \( LCC \). Clearly, negative values at year 0 correspond to the ERM and strengthening investment costs; the intercept with the axis of time represents the discounted payback time, i.e., the number of years needed to make initial costs (for energy or structural retrofit) equal to year-by-year gathered savings. For example, Figure 4a and b show the overall trend of \( LCC_{\text{sav}} \) as a function of time for Spoleto site, considering the energy and strengthening retrofit effects, respectively.

Firstly, it can be observed that the inclusion of cost-optimal energy retrofit costs within the seismic-induced EAL computation causes an increase of the payback time of approximately 10 years (black-line in Figure 4a). In practice, the economic effort required to improve the energy efficiency of the building might be partially neutralized by yearly seismic losses. When considering only the effect of the different strengthening techniques on the seismic EAL, it turns out that the selected techniques (characterized by different initial costs) produce three different payback time values (ranging between 15 and 20 years); among these, the technique having the smallest ratio between initial cost and payback time has been selected as the most cost-effective and implemented in combination with the cost-optimal ERM.
Figure 5 summarizes the discounted payback times resulting from Step (4) and Step (5) and for the three building sites investigated. In two of the three building site cases, the combined energy-structural approach was more cost-effective if compared to the only energy retrofit including EAL evaluated throughout the building lifetime.

![Figure 5. Discounted payback time for the three different building sites](image)

The coupling with structural retrofit is able to avoid economic losses associated with ERMs implemented into the structure. Indeed, the discounted payback times resulting from the combined approach were significantly reduced depending on the particular site. In addition, for Benevento site, the discounted payback time of the combined approach was higher than the case of the retrofit with only ERMs. This was a consequence of the investment cost; indeed, in that case the investment cost for the ERMs was significantly lower than that of the seismic retrofit.

5. Concluding remarks
The present paper has proposed a life-cycle based multi-step approach aiming to reliably design combined energy and structural retrofit by considering expected economic losses due to the seismic risk. This methodology is novel in the context of sustainability evaluation of retrofit interventions on existing buildings since it integrates energy optimization with the analysis of structural performance over the building life cycle. The outcomes of the approach enable addressing the selection of proper energy-structural retrofit measures by considering the overall cost-effectiveness of the retrofit itself; this might have important implications especially for retrofitting large strategic infrastructures, such as existing public schools, as well as for the selection of national policies or incentives.

Future developments of this research regard the refinement and validation of the methodology including also environmental aspects.

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