

Chapter 9

Energy Efficiency and Seismic Resilience: A Common Approach

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Abstract To the present date, building retrofit and enhancement interventions tend to focus on either energy efficiency or seismic resilience techniques, highlighting the lack of consistent language and understanding across both fields, as well as the disconnection among stakeholders that arises from the development of seismic risk mitigation independently of sustainable development goals. Although extensive know-how can be identified in both areas, efforts for its joint consideration presented in the literature are based on the evaluation of environmental impacts of expected repairs due to seismic action over a period of time, neglecting the potential of energy efficiency enhancements and, more importantly, the possible benefits of an integrated investment strategy. This chapter presents a proposal for the integrated assessment of energy efficiency and earthquake resilience, according to which environmental and seismic impact metrics are translated into common financial decision-making variables. In this context, similarly to what is a common practice when evaluating the energy and environmental performance of buildings, discrete classes of both earthquake resilience and energy efficiency are proposed, providing a consistent proxy for building classification—*green and resilient indicator (GRI)*—as a function of mutual performance parameters. The findings of this chapter highlight the fact that it is possible to directly compare energy efficiency and seismic resilience from a common point of view, as it is plausible to assume the *green* and *resilient* counterparts of the *GRI* classes as a proxy for investment return potential. In addition, it is verified that the *benefit* of a given intervention can only be maximized up to the point in which an additional investment does not result in increased performance. Thus, an integrated approach shall always be

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advantageous with respect to the investment in only *earthquake resiliency* or *energy efficiency*, devising an investment strategy in a way that simultaneously maximizes “individual” benefits and its integrated result.

9.1 Introduction

Resources are usually the absent guest in all tables where the issue is to define the performance level to be met when designing new structures and much more so when the issue is the upgrading of existing constructions (Calvi 2013). However, at present, most interventions for building enhancement focus either on energy efficiency or seismic strengthening, considering the maximization of benefits independently of the integrated correlation between both variables.

While the application of performance-based concepts has been applied to the specific case of seismic design using a decision support system (e.g., Caterino et al. 2008; Zareian and Krawinkler 2012), little attention has been devoted to existing buildings to what concerns seismic resilience (Calvi 2013) and energy efficiency counterparts.

The aforementioned circumstances highlight the necessity of a sensitivity study that enables the addressing of potential benefits arising from an integrated approach including disaster risk management and climate adaptation. With a starting point in state-of-the-art knowledge and best practices in both aspects of building assessment and enhancement, the present document intends to provide a proposal for an innovative model that combines the mentioned interventions, in order to maximize the financial and technical efficiency of the two practices under a comprehensive methodology. In this context, any prioritization scheme obviously implies the possibility of correcting performance level and time constraints to available resources, thus giving an answer to the problem of comparing resources and needs (Calvi 2013). Nonetheless, sounder approaches allow the definition of prioritization schemes that somehow associate the target performance to a level of “risk rating” (e.g., Grant et al. 2007). Since the obstinate pursuing of a predetermined level of performance may result in irrational cost-benefit ratios, the herein proposed model shall provide guidance on why and in which situations should energy efficiency and disaster-resilient practices be integrated and, more importantly, how should interventions be prioritized to achieve the highest return to investment.

Three real case study buildings representing distinct typologies—residential, educational, and healthcare—are modeled and analyzed in order to demonstrate the correlation between cost and benefit associated with the joint investment in energy sustainability and seismic resilience. To this end, climate and seismic hazard are established for both the original design locations and additional sites, considered in order to replicate conditions different from that of the original design. In this context, it is decided to verify the validity of such methodology through the analysis of the mentioned representative buildings, allowing the definition of the appropriate guidelines for a definitive model.

9.2 State of the Art

9.2.1 Earthquake Resilience

A commonly accepted framework in the assessment of building-specific resilience to seismic action is established in a formulation derived from the SAC project (Cornell et al. 2002) and included in different forms in FEMA and ATC documents (Calvi 2013), according to which seismic risk is evaluated in a probabilistic manner. This formulation addresses several types of uncertainties conjugated in a triple integral, as follows:

$$\lambda [DV|D] = \iiint p [DV|DM, D] \cdot p [DM|EDP, D] \cdot p [EDP|IM, D] \cdot \lambda [IM|D] dIM \cdot dEDP \cdot dDM$$

It is understood that such formulation, which will not be herein discussed in detail—addressing the reader to the works of Porter et al. (2002) and Haselton et al. (2007)—may appear quite difficult and inapplicable. However, as depicted in Fig. 9.1, it is rather a conventional formal expression that combines four steps of analysis—seismic hazard, structural response, damage assessment, and loss estimation—each one characterized by epistemic and aleatoric uncertainties associated with the ultimate estimation of $\lambda [DV|D]$, the rate of exceedance of a

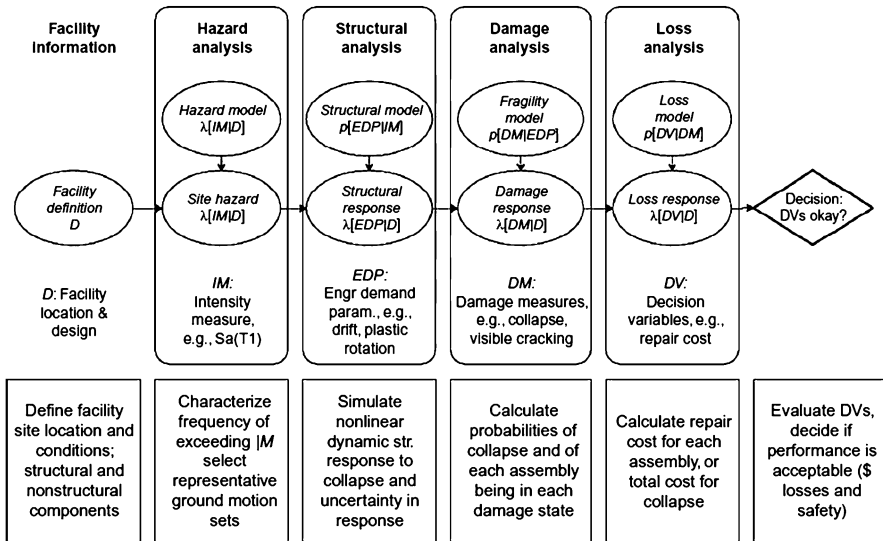


Fig. 9.1 PEER methodology to estimate losses in a probabilistic framework (Porter et al. 2002; Haselton et al. 2007)

certain decision variable (DV) that allows understanding risk through a probabilistic standpoint, for a given reference time span.

9.2.1.1 Multi-criteria Decision and Seismic Risk Mitigation

The inclusion of probabilistic *seismic risk* assessments into the multi-criteria decision for building intervention is not extensively available in the literature. In most cases in which such criteria are considered, the associated parameters are related to the deterministic seismic intensity at which a certain damage is attained, rather than with the probabilistic building expected *loss* due to seismic-induced damage over a given time period. In the work of Caterino et al. (2008, 2009), whose philosophy is also applied in the research campaign of Tesmafatian et al. (2010), the *seismic risk* decision variables are incorporated into “significant damage risk” and “damage limitation risk” evaluation criteria for different retrofit techniques. These are designated by the author as the “risk of significant damage attainment” and “risk of nonstructural damage to repair,” respectively, reflecting, in fact, the influence of an intervention scheme in the building resistance, expressed as the deterministic level of seismic intensity at which the two established damage states are achieved.

Notwithstanding the above, seismic risk analysis has been widely employed in single criteria selection of retrofit techniques by means of an accepted risk tolerance and respective decision-making tool, generally reported as *cost-benefit* analysis, *life-cycle* costing, deterministic and stochastic *net present values*, or *multi-attribute* utility-based procedures (Tesmafatian et al. 2010). However, in addition to the fact that only economic factors are considered, all the previously mentioned sensitivity analyses depend on the definition of “performance levels” and “retrofitting objectives,” which reflect the extent to which the building intervention will upgrade its response to a given level of seismic intensity.

Most approaches to the definition of performance levels are derived from the scheme originally proposed for new constructions in the Vision 2000 document (SEAOC 1995). This document introduced the concept of varying the expected performance for different return period ground motions as a function of the relevance of the facility. The resulting matrix is well known and not essential in this context, while the numerical definition of four intensity levels in terms of their return period or probability of exceedance—*frequent* (50 % in 30 years), *occasional* (50 % in 50 years), *rare* (10 % in 50 years), and *very rare* (5 % in 50 years)—is still used as a possible reference. Even more relevant is the attempt of numerically defining the expected performance as a function of a single parameter, the inter-story drift, as shown in Table 9.1.

The concepts presented in the Vision 2000 document were elaborated and extended in FEMA 356 (2000), but the next conceptual step was essentially due to the SAC project (Cornell et al. 2002), where the modeling of uncertainties was proposed, which inspired the development of a series of ATC documents culminated with the ATC (2011), still in a draft form.

Table 9.1 Vision 2000 (SEAOC 1995) definition of performance levels

Performance level	Performance description	Story drift (%)
Fully operational	Continuous service, negligible damage	0.2
Operational	Safe for occupancy, light damage, repairs for nonessential operations	0.5
Life safety	Moderate damage, life safety protected, repair possible but may be impractical	1.5
Near collapse	Severe damage, collapse prevented, falling of nonstructural elements	2.5

		Target Building Performance Levels			
		Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
Earthquake Hazard Level	50%/50 year	a	b	c	d
	20%/50 year	e	f	g	h
	BSE-1 ≈10%/50 year	i	j	(k)	l
	BSE-2 ≈2%/50 year	m	n	o	(p)

Fig. 9.2 Relationship between earthquake hazard and building performance, from FEMA 356

Currently, the specifications for the required structural response improvement can be found in several commonly employed code standards for building assessment. These include the European EC8, part 3 (CEN 2005); FEMA 356 (2000) and ASCE 41-06 (2006), used in the United States; and the New Zealand Society of Earthquake Engineering—NZSEE (2006)—recommendations on “earthquake risk buildings.”

According to the aforementioned code standards, the building assessment and retrofit are required to comply with specific damage states considered acceptable for established seismic action levels. In this context, following the previously mentioned prescriptions primarily established by the Vision 2000 document, it is a common practice to expect the building to perform with moderate damage for a “current” seismic event, generally characterized by a 10% probability of being exceeded in 50 years and sustain collapse under a “rare” event with a usually accepted 2% probability of being exceeded in 50 years, as stated in FEMA 356 and ASCE 41-06. Accordingly, as presented in Fig. 9.2 (reproduced from FEMA 356), this philosophy defines a *Basic Safety Objective* (BSO) that approximates the earthquake risk to life safety levels traditionally considered acceptable.

Seismic codes for the earthquake-resistant design and retrofit of structures are fundamental for the mitigation of seismic risk. As duly mentioned, codes provide guidance for engineers on the analysis of the effects of earthquake ground motions on structures, as well as on the required configuration and detailing for improved seismic performance. However, the experience of the 1994 Northridge earthquake and the 1995 Great Hanshin (Kobe) earthquake demonstrated that both economic losses and human casualties could be considerable, even if the non-collapse objective had been met for many structures (Bommer and Pinho 2006).

It is thus clear that an approach based on code-defined performance objectives for specific levels of ground motion intensity is unable to fully take into account the seismic hazard characteristics of the site in question, as well as the expected *loss* for a period of time (i.e., the expected level of *loss* in a period of time arising from a probabilistic seismic risk analysis).

From a design point of view, a risk-based methodology has been an object of research, such as the risk-targeted approach presented by Luco et al. (2007), which considers only the no-collapse limit state in a probabilistic formulation for definition of design seismic demand. Furthermore, the degree of seismic detailing required to meet performance objectives other than collapse at lower intensities is investigated by Bommer et al. (2005), by means of an iterative procedure to determine the benefit of different strengthening scenarios in resulting earthquake *losses*.

In addition, Crowley et al. (2012) developed a proposal for calibration of codes for performance-oriented design, according to the quantitative comparison of incremental costs of improving the seismic resistance of a building with the associated avoided *losses*, expressed as the expected annual loss for a given region (northwest area of Turkey). The proposed procedure presents a similar philosophy to a methodology developed at the PEER (Porter 2003) for probabilistic-based seismic design, taking into account the *loss* in terms of costs, casualties, and downtime for increasing levels of hazard from a cost-benefit viewpoint. However, the PEER approach is applicable only for building-specific design and thus does not consider the convolution of hazard and vulnerability on an urban scale, such as the work of Crowley et al. (2012).

To what concerns the seismic assessment and retrofit of existing buildings in the context of a risk-based methodology, the most recent effort is related to the development of *next-generation performance-based seismic design procedures and guidelines for application to new and existing buildings*, under the scope of ATC-58 project. As stated in the related publication FEMA P-58-1 (FEMA 2012), the next-generation design (and assessment) procedures address performance objectives as statements of the acceptable risk of incurring casualties, direct economic *loss* (repair costs), and occupancy interruption time (downtime) associated with repair or replacement of damaged structural and nonstructural building elements. Accordingly, the building performance is determined through a complete seismic risk analysis, combining all its features for an alternative and more meaningful way of communicating risk with stakeholders and other decision-making entities with regard to improvement of seismic resilience of buildings.

As additionally stated in FEMA P-58-1 (FEMA 2012), from a decision-making point of view, time-based assessments can be used to provide the average annual value of *loss*, which is particularly useful in the context of *benefit-cost* studies for different retrofit strategies or building design. Hence, as more thoroughly presented in the remainder of this document, the average annual value of a performance measure—*loss* ratio—is considered as input to determine a reasonable investment for improved seismic resistance in a building, comparing the *net present value* (NPV) of average annual costs that are avoided throughout the building life cycle, versus the costs associated with providing an enhanced seismic resistance.

9.2.2 Energy Efficiency

Starting from the well-known reality in which buildings nowadays generate approximately 40 % of the world’s carbon emissions, it is clear how the construction of more environmentally friendly buildings and the renovation of existing buildings will play a critical role in reducing these effects. Furthermore, it is generally recognized that a sustainable policy in the construction field is strongly advised.

Sustainability can be defined as the ability to meet the needs of the present without compromising the ability of future generations to meet their own requirements, creating and maintaining the conditions under which humans and nature can exist in productive harmony, making sure that we have and will continue to have the water, materials, and resources to protect human health and our environment. In this context, green building philosophy is the practice of creating structures and using processes that are environmentally responsible and resource efficient throughout a building’s life cycle.

The market related to green construction has grown dramatically since the year 2000, and it is forecasted to continue to grow, despite of the expected decline in the overall construction market. It has been estimated that the total value of green construction was \$10 billion in 2005, increasing to \$49 billion by 2008. In addition, by the end of this current year, it estimates that the market could grow to as much as \$96–140 billion (USGBC 2011).

As building owners select more environmentally friendly designs for their buildings, the demand for “green” services will continue to rise. Similarly, owners are aggressively retrofitting buildings in their existing portfolio to take advantage of reduced operating costs and to maintain or increase the value of their property. To this end, efficient energy use, sometimes simply called *energy efficiency* (EE), is the goal to reduce the amount of energy required to provide products and services. Taking into account that since 1994 energy prices have raised drastically (more than 30 %), it is clear that reduction of consumption for a building must be one of the principal aims in design and retrofitting. It is strategic though to have in mind what is going to be the return period or the break-even point related to the initial investment done to enhance the building efficiency.

For building owners, energy efficiency offers the opportunity to lower operating costs, enhance building quality, and increase financial returns. Standards such as LEED—a green building tool that addresses the entire building life cycle recognizing best-in-class building strategies—and Energy Star, an Environmental Protection Agency voluntary program to identify and promote energy-efficient products and buildings in order to reduce energy consumption, reflect and foster increasing interest in making buildings more energy efficient. However, the vast majority of EE opportunities remain unfinanced due to split incentives, insufficient credit, and limited data, among other reasons (USGBC 2011).

As with virtually all economic problems, the economics of energy efficiency is at its heart a question of balancing of costs and benefits. For the individual energy user, this involves weighting the higher initial cost of purchasing energy-efficient

solutions with the expected benefits of future cost savings. Since energy efficiency is strictly related to environmental pollution associated with energy production—particularly carbon dioxide emissions from fossil fuels—it is important to realize in advance not only the cost-benefit in terms of economic savings but also in terms of the positive environmental impact, which is obviously an important benefit for the all community.

9.2.3 *Integrated Approach*

Given the fact that natural hazard risk mitigation has evolved independently of consideration for sustainable development goals, there tends to be a disconnection among stakeholders, as well as lack of consistent language and understanding across the field of natural hazard mitigation and those embracing sustainable development concepts (Tapia and Padgett 2012). Recent disasters have highlighted the need for a paradigm shift that allows the understanding of buildings' life-cycle costs from the “earthquake-induced environmental impact” point of view (Comber et al. 2012), so as to develop an overarching framework that enables the consideration of both perspectives.

It is important, in the present context, to adequately relate seismic performance and the economic/environmental benefits that can be realized by performance-based design and assessment procedures such as the ones presented in Sect. 9.2.1.1 of the present document. Hence, a simple way of approaching the problem is to consider the influence of the design/retrofit on seismic risk in such a way that enables the building's life span that is relied upon from an environmental point of view. Although valid from a descriptive perspective, the latter is clearly incomplete, since rather than the simple influence of building collapse into the expected environmental performance over a given expected period, the goal of an integrated approach is to adequately incorporate seismic risk analysis and its environmental impacts into a life-cycle assessment, considering the probabilistic distribution of possible building damage over a period of time.

A common practice in conducting an environmental life-cycle assessment (LCA) on a building includes a consideration of the impacts stemming from the first construction. Considerations are also often made for additional impacts stemming from building maintenance and energy usage throughout its life span, but very rarely the potential additional environmental impacts that could arise from repairing or demolishing after a natural disaster are included in an LCA, if ever at all (Comber et al. 2012). To this end, discussions have begun to surface in the literature that highlight the conceptual environmental impacts of individual buildings (Kneer and Maclise 2008a, b) and regional impacts (Burton et al. 2011) resulting from seismic damage. In fact, in areas of high seismicity, an opportunity exists for the structural engineering community to carefully consider the level of risk and employ seismic damage mitigation strategies that effectively minimize the probabilistic integrated life-cycle impacts.

Frameworks incorporating natural hazard risks and their mitigation into the LCA to assess sustainability of infrastructures have recently begun to emerge. Itoh et al. (2005) proposed a model to determine life-cycle environmental impacts and costs from construction and maintenance phases as well as from losses and recovery after an earthquake event, using CO₂ emissions as the environmental impact indicator. In addition, natural hazard considerations were integrated into the LCA to quantify environmental among other metrics of sustainability (social and economic) by Padgett et al. (2009) and expanded by Dennemann (2009). The sustainability metrics considered in the latter for the specific case of non-seismically designed bridges are life-cycle cost (due to repair/replacement from seismic exposure), functionality/downtime and expected number of fatalities due to bridge failure over structure life, and energy usage associated with repair and reconstruction of damaged structures.

Two recent studies by Ghosh et al. (2011) and Tapia et al. (2011) address a number of shortcomings of the aforementioned works. These studies propose frameworks for quantifying life-cycle cost, embodied energy, and CO₂ emissions for structures subjected to aging, deterioration, and seismic action. LCA is thus simplified by only including the repair and replacement phases of these structures, although in a probabilistic fashion. The inherent results underscore the extent to which natural hazard mitigation can reduce environmental- and economic-related sustainability metrics as well as the importance of their evaluation (Tapia and Padgett 2012).

The aforementioned research campaigns constitute valid, yet simplified, attempts to join seismic risk and environmental impacts in a comprehensive integrated approach. However, they are based on the specific case of bridges, which greatly differ from the object of this study in the structural parameters involved.

A recent study developed by Comber et al. (2012) has led to the development of a method for quantifying the impacts of seismic damage to the full building system including nonstructural components and contents that maintains a level of approximation considered appropriate given the nature of the two procedures that are being paired together: seismic *loss* estimation and LCA. The seismic *loss* assessment methodology selected for incorporation into the authors' approach is the Advanced Engineering Building Module (AEBM) of the Hazards US (HAZUS) methodology, which was developed by FEMA (FEMA 1999). The latter is explored in assessing the expected seismic *losses* in building components and contents, paired with an extensive component database that enables the link between component damage and the correspondent environmental impact. A probabilistic seismic hazard assessment was conducted in order to annualize the environmental impacts due to seismic damage for a case study building (with different design schemes), expressed in terms of equivalent embodied annual carbon footprint. It seems clear that the presented methodology does not take into account energy efficiency in the consideration of the annualized environmental impact. Differently, it incorporates such impacts as resulting from the expected seismic damage (and inherent repairs), excluding the carbon footprint associated with consumed energy over the same time period. However, comparing impacts from annualized seismic damage with

its energy use counterpart is a possible and valuable exercise, as exemplified in the work of Comber et al. (2012). In fact, considering the energy efficiency improvement currently being targeted by the US federal government, buildings such as the ones assessed in the referred study are expected to benefit from a 20% decrease in energy usage through efficiency enhancements (DOE 2006), which is in the same order of magnitude as the probabilistically realized reduction resulting from a seismic retrofit scheme, as verified by Comber et al. (2012), for a specific case study. According to the latter, this case study shows that in some buildings, be them new construction or seismic retrofit projects, the increase in initial environmental impact that can result from constructing the building to an enhanced seismic performance objective may result in a net overall reduction throughout the building's life span, due to the achieved reduction in the expected annual level of CO₂ emissions resulting from seismic damage repair operations. Therefore, in order to achieve a more accurate sense of what type of seismic system should be used to minimize a building's full life-cycle impact, a consideration of the expected seismic damage over time should be incorporated into the LCA (Comber et al. 2012).

From a building performance analysis and *loss* assessment point of view, the previously presented HAZUS methodology imparts a number of simplifications that limit the applicability scope of the proposed methodology. In this context, the recently proposed ACT-58 method (FEMA 2012) for performance-based seismic design and retrofit of buildings constitutes a comprehensive and generally applicable methodology for the determination of building-specific *loss* due to seismic action. Thus, the purpose of the related ATC-86 project (Court et al. 2012) is to develop a performance-based environmental impact assessment methodology to integrate into the P-58 procedures and its companion Performance Assessment Calculation Tool (PACT). Moreover, the ATC-86 approach should account specifically for the environmental repercussions of the probable earthquake damages and repairs predicted by the P-58 method (Court et al. 2012).

Life-cycle assessment provides a natural framework for this purpose, traditionally accounting for environmental impacts over an entire building life cycle from cradle to grave. Although the latter does not typically account for earthquake effects, it incorporates it by taking advantage of the P-58 powerful tool for predicting earthquake damage and its consequences. Hence, it offers a unique opportunity to quantify the probable earthquake impacts and add them to the full building life-cycle assessment. It consists of a procedure for measuring the environmental performance of products or processes over their full life cycles from cradle to grave. In this context, environmental metrics typically include global warming potential, embodied and operational energy, natural resource consumption, waste generation, and a broad range of environmental pollutant impacts. To this end, the International Standards Organization in its ISO 14040 series (ISO 2006a, b) provides appropriate life-cycle assessment guidelines (Court et al. 2012).

As in the case of the work of Comber et al. (2012), the environmental implications of retrofit interventions under the scope of a life-cycle assessment are

determined according to life-cycle inventories (LCIs) that list all the energy flows associated with material components during their life cycle, quantifying average material emissions for different material processes. In the context of the P-58 methodology, the environmental impact measures are combined with a bill of materials and processes associated with earthquake damage cleanup and repair, so as to generate measures for the building as a whole. Such matters will be addressed in the P-58 and ATC-86 methodologies (Court et al. 2012), in order to establish how and to which extent design or retrofit of buildings for better seismic performance could reduce the damage-related impacts, depending on the rate of occurrence of damaging earthquakes during a building's service life.

It should be mentioned, however, that the aforementioned project (ATC-86) is currently in a development stage, which makes the access to its definitive conclusions and proposed methodology unavailable.

9.3 Seismic Resilience and Energy Efficiency: A Model for a Common Approach

9.3.1 Scope Definition and Initial Assumptions

Following the literature review examples analyzed in Sect. 9.2.3, a proposal for the integrated assessment of energy efficiency and earthquake resilience is presented. As aforementioned, the more recent efforts to account for both types of demands tackle the problem of integrating the building environmental performance as a secondary variable, depending on the level of earthquake *loss*. Under this assumption, the inherent performance measures reflect the annualized carbon footprint due to the expected level of repair or retrofit operations resulting from earthquake damage.

Although the above can provide valid information in the context of a decision-making process, it does not directly reflect the main subject under scrutiny, i.e., the potential economic benefits of an integrated investment approach on seismic and energy efficiency building improvement. To this end, the consideration of a multidisciplinary procedure in which environmental and economic variables are incorporated in the investment decision parameters is tackled in this document, as further presented.

In the context of seismic *risk* assessment, one of the most important outputs is the frequency that the possible levels of *loss* will be equaled or exceeded on an annual basis, as illustrated in Fig. 9.3, in which the so-called *loss exceedance curve* is graphically represented.

However, even though particularly useful information can be derived from the latter, the communication of seismic *risk* with stakeholders, insurance companies, governmental agencies, and other decision-making entities requires the definition of a performance metric that can adequately translate the mentioned information in a concise and readily applicable fashion. Accordingly, the concept of *expected*

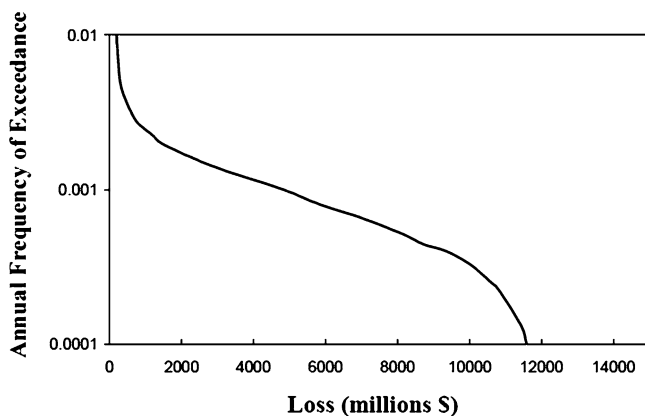


Fig. 9.3 Illustrative example of a loss exceedance curve

annual loss is usually considered as the final output of the assessment, calculated as the expected value of the referred *loss exceedance curve*, i.e., the average value of *loss* that a building (or group of buildings) will sustain annually over its life span due to seismic action.

According to the aforementioned, by approaching the present problem simply from a seismic resilience point of view, the selection of *expected annual loss* as a comparison parameter for a cost-benefit analysis seems particularly adequate. As subsequently enunciated, an analog reasoning can be employed when incorporating the energy efficiency analysis in the equation, by defining an *energy expected annual loss* (EAL_E) that can directly be compared with its seismic counterpart (EAL_S). Thus, if one chooses to consider the building value (or cost to replace) as the common ratio denominator, the *energy loss* can be determined as the ratio between cost of consumed energy and building value, as follows:

$$\text{seismic loss} = \frac{\text{cost to repair}}{\text{total building value}}; \quad \text{energy loss} = \frac{\text{energy cost}}{\text{total building value}}$$

As further presented in detail (see Sect. 9.3.2.1), it is common practice to classify building energy efficiency according to its expected annual energy consumption, which is of particular interest in the present context. Accordingly, the mentioned value of *energy expected annual loss* (EAL_E) can be determined as the ratio between the average annual cost of consumed energy and total building value, rendering a compatible base of analysis and comparison:

$$EAL_E = \frac{\text{mean annual energy cost}}{\text{total building value}}; \quad EAL_S = \frac{\text{expected seismic loss}}{\text{total building value}}$$

9.3.2 Framework Proposal

The herein presented framework consists of an initial model for a cost-benefit analysis methodology to test different scenarios for tackling energy efficiency and earthquake resilience. Starting from a classification system according to both “green” and “resilient” indicators, initial condition and “upgraded” configurations are considered and building performance evaluated.

The investment required for a given building performance improvement is related to its benefit over time through appropriate indicators and return ratios, allowing for the evaluation of different possibilities for strengthening and refurbishment, based on current best practices. The appraised results shall therefore lead to the identification of potential financial benefits from implementing an integrated approach, as well as pointing out possible challenges to be faced in its practical application.

9.3.2.1 Building Performance Classification

In order to establish the base for building assessment and improvement, a consistent proxy for building classification is required. To do so, building performance—from earthquake resilience and energy efficiency points of view—shall be divided into two directly comparable and cumulative components of a comprehensive *green and resilient* indicator (*GRI*).

The main advantage of such classification is the possibility of separately analyzing the building in terms of earthquake resilience and energy efficiency, determining the advantages and associated costs of improving its capacity to a preestablished level of performance, determined by the *GRI*. As proposed in the work of Calvi (2013), similarly to what is done when evaluating the energy and environmental performance of buildings, discrete classes of earthquake resilience might be defined, in accordance with the predicted value of *expected annual loss*. Therefore, since both components of *EAL* are expressed in terms of analog quantities (see Sect. 9.3.1), the cost and benefit of the separated approaches can be conjugated.

For the purpose of the present exercise, as a starting point, the preliminary classification system proposal is based on a comprehensive approach in which the energy efficiency classification in Italy (D.P.R. 2009), which is based on European legislation on the matter, is further “translated” into categories based on the previously enunciated *energy expected annual loss* (EAL_E). The Italian building classification and its regional specifications (DGR Emilia-Romagna n.1366/2011) provide indications for different types of buildings, according to the total (annual) energy consumption due to heating and water supply. As presented in Fig. 9.4, eight classes of performance are established for residential buildings. The indicator used (EP—primary energy) is the amount of energy needed to heat the building, according to the calculation criteria of the UNITS 11300 (2008a, b, 2012), expressed in kWh/m².

Fig. 9.4 Italian building energy classification system, Emilia-Romagna region (DGR Emilia-Romagna n.1366/2011) for residential buildings

Energy Class	Residential - kWh/m ²
■ A+	$EP_{tot} < 25$
■ A	$25 < EP_{tot} < 40$
■ B	$40 < EP_{tot} < 60$
■ C	$60 < EP_{tot} < 90$
■ D	$90 < EP_{tot} < 130$
■ E	$130 < EP_{tot} < 170$
■ F	$170 < EP_{tot} < 210$
■ G	$EP_{tot} > 210$

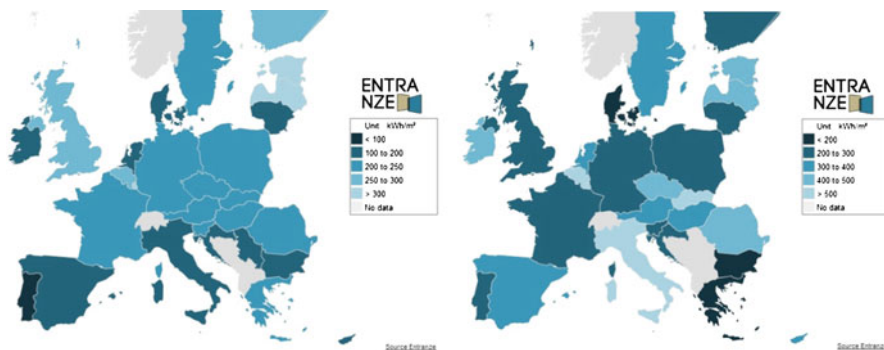


Fig. 9.5 European countries’ average annual energy consumption for residential (*left*) and non-residential (*right*) buildings

As presented in Fig. 9.5, the aforementioned classification satisfactory agrees with the annual energy consumption data from the European residential building portfolio, provided by the ENTRANZE project, financed by the European Union (ENTRANZE project: <http://www.entrance.eu/>), in which the 27 EU members are scrutinized. The referred data corresponds to the year 2008, so as to consider data not affected by the 2009 international financial and economic crisis, as stated in the project data interface (ENTRANZE project database interface: <http://www.entrance.enerdata.eu/>).

However, to what concerns the nonresidential building data, it is clear that the classes presented in Fig. 9.5 are not able to adequately characterize the expected levels of building energy consumption. Thus, in order to outline a more representative set of classification indicators, taking into account both the residential classification system (Fig. 9.4) and the information presented in Fig. 9.5, the following energy classes are considered:

Taking into account the latest indication of average construction cost values in Europe, provided by the European statistical bureau—EUROSTAT—in its report *A decade and more of monthly construction statistics* (Fassbender 2007), and current

values of energy cost (EUR/kWh), the energy classes presented in Fig. 9.6 can be expressed in terms of EAL_E ratios, as follows:

$$\begin{aligned}
 EAL_E &= \frac{\text{mean annual energy cost [EUR]}}{\text{total building value [EUR]}} \\
 &= \frac{\text{mean net annual energy cost [EUR/m}^2\text{]}}{\text{construction cost [EUR/m}^2\text{]}}
 \end{aligned}$$

where the *mean net annual energy cost* stands for the average cost of consumed energy divided by the building area and construction cost is represented by the ratio between building value (or “cost to replace”) and its construction area. Therefore,

$$EAL_E = \frac{EP_{TOT} [\text{kWh/m}^2] \cdot \text{unit energy cost [EUR/kWh]}}{\text{construction cost [EUR/m}^2\text{]}}$$

According to the above, the *GRI* classification, particularly in what concerns its *green* indicator, can be considered as presented in Fig. 9.7.

Given the fact that the values obtained in the above procedure for the *green* indicator can furthermore be considered reasonable assumptions from an earthquake resilience classification point of view, to what concerns the typical values of EAL_S

Fig. 9.6 Adopted energy classification system, for residential and nonresidential buildings









Energy Class	Residential -kWh/m ²
 A+	$EP_{tot} < 25$
 A	$25 < EP_{tot} < 40$
 B	$40 < EP_{tot} < 80$
 C	$80 < EP_{tot} < 130$
 D	$130 < EP_{tot} < 170$
 E	$170 < EP_{tot} < 250$
 F	$250 < EP_{tot} < 400$
 G	$EP_{tot} > 400$

Fig. 9.7 *GRI* classification proposal for energy efficiency









Green Indicator	EAL_E (%)
 A+	$EAL < 0.50$
 A	$0.50 < EAL < 0.75$
 B	$0.75 < EAL < 1.50$
 C	$1.50 < EAL < 2.50$
 D	$2.50 < EAL < 3.50$
 E	$3.50 < EAL < 4.50$
 F	$4.50 < EAL < 7.50$
 G	$EAL > 7.50$

Fig. 9.8 *GRI* classification proposal for energy efficiency and seismic resilience

GRI Classification (Green and Resilient Indicators)	EAL_E or EAL_S (%)
■ A+	$EAL < 0.50$
■ A	$0.50 < EAL < 0.75$
■ B	$0.75 < EAL < 1.50$
■ C	$1.50 < EAL < 2.50$
■ D	$2.50 < EAL < 3.50$
■ E	$3.50 < EAL < 4.50$
■ F	$4.50 < EAL < 7.50$

registered for reinforced concrete buildings, it is decided to assume a unique *GRI* for both seismic performance and energy efficiency assessments, for simplification purposes, as a function of EAL_S and EAL_E , respectively. Thus, the classes A+ to G presented in Fig. 9.7 are at this point referred to as parameters of the *GRI* (green and resilient indicator), as definitively presented in Fig. 9.8.

As previously mentioned, the presented building classification intends to serve the purposes of the present exercise and shall, therefore, be considered as a preliminary indication that requires further refinement. Nonetheless, the presented proposal consists of a valid preliminary proxy for building energy efficiency and seismic resilience, allowing for a cost-benefit analysis of the advantages/shortcomings of an integrated *GRI* improvement approach, as further presented.

9.4 Seismic Resilience and Energy Efficiency: Model Application

9.4.1 Case Studies

Three buildings are analyzed according to different scenarios of initial design, seismic and energy efficiency demands, and strengthening/refurbishing possibilities, so as to assess the influence of the interested variables in building performance over its expected life cycle. Moreover, a general overview of the advantages/shortcomings of an integrated approach, as well as the circumstances in which its application is deemed to be beneficial, is presented, reflecting the influence of different seismic and energy efficiency demands in the buildings' *expected annual loss* (EAL_E and EAL_S), according to the selected "building-specific environment":

- Location of the building (climate zone in which the building is constructed and seismic hazard at the site)
- The function of the building itself (residential, healthcare, and public administration, in the present case)



Fig. 9.9 3D representation of case study A

It shall furthermore be mentioned that, for the purpose of assessing the building performance in terms of both earthquake resilience and energy efficiency in conditions different from those foreseen in design stages, additional locations have been considered. Therefore, in addition to the design locations presented in Sects. 9.4.1.1, 9.4.1.2, and 9.4.1.3, supplementary hypothetical building locations have been established for each of the further presented case studies, as defined by the climate and seismic hazard characteristics of Istanbul (Turkey), Yerevan (Armenia), and Messina (Italy).

9.4.1.1 Case Study A

The first case study refers to a residential complex constructed in Pavia, Italy, constituted by five seven-story buildings with a 30 m wide square plan configuration, as illustrated in Fig. 9.9. Each building features an inner courtyard of 18 m on each side bounded by a gallery that provides access to individual apartments by vertical connections.

The reinforced concrete structural system complies a solution in which precast columns are conjugated with cast-in-place concrete slabs and central core. Furthermore, all floors are made of reinforced concrete solid slabs and the cover is made of metal carpentry.

The “skin” of the buildings has been provided with several devices in order to minimize the heat loss. The final exterior surface, constructed of pre-colored silicate paste, guarantees the minimization of thermal bridges around the casing, ensuring the total continuity of technological heat-insulating layers in the classic points of disconnection. On the upper floors, a ventilated wall with aluminum substructure and mantle brick was implemented, in order to replace the thermal coat. In addition,



Fig. 9.10 3D representation of case study B

the windows made of PVC maximize energy performance and ensure at the same time lightness and maneuverability due to its reduced weight.

The heat and air conditioning system is based on the use of geothermal energy, resorting to water-to-water heat pumps that provide hot and cold water for heating, hot water for sanitary use, and refrigerated water. In addition, an integrated photovoltaic system has been implemented on the roof of the buildings, allowing the production of a peak power of approximately 195.5 kWp. The electricity produced is used for the maintenance of heating, cooling, and domestic hot water production.

Each apartment is provided with a satellite counter to estimate the real consumption of heat and cold water, together with electricity, and a building management system is installed in order to overview and control the functionality of the all generation systems.

9.4.1.2 Case Study B

Case study B represents a school constructed in Emilia-Romagna, Italy (Fig. 9.10) in which the structural solution establishes an approach toward the optimization of the building process. It involves the construction of a continuous reinforced concrete foundation slab, above which the building structural system will be implemented. The lateral load-resisting system is materialized by composite cast-in-place columns and precast reinforced concrete beams in longitudinal and transversal directions. The columns are circular with outer jacket in stainless steel having an outer diameter of 600 mm and thickness equal to 6.3 mm, which fulfills the function of both formwork and confinement.

Particular attention was given to the building envelope concerning the choice of thermal performance of materials. The window frames proposed are highly efficient, and matt surfaces are materialized by pre-insulated sandwich panels with the addition of mineral wool and counter wall. In addition, highly efficient heat pumps are used for winter and summer acclimatization, in order to achieve an



Fig. 9.11 3D representation of case study C

energy class of excellence. The technological solutions are all characterized by a high standard of quality, through the use of leading brands leader in the field of air conditioning and heating.

9.4.1.3 Case Study C

Case study C refers to a healthcare building constructed in Milan, Italy, illustrated in Fig. 9.11 by a 3D building representation. The building is constituted by a main body of four floors inscribed in a plan configuration of approximately $104 \times 70 \text{ m}^2$ and total height of 20.1 m.

The vertical elements and lateral load-resisting system are materialized by reinforced concrete columns and walls of variable dimensions.

The building envelope is designed in order to obtain an A building energy class, using high-performance technology solutions in both parts of opaque shell, as well as low-emission windows with argon gas for the transparent casing. The heat and air conditioning system is based on the use of geothermal energy, resorting to water-to-water heat pumps that provide hot and cold water for heating, hot water for sanitary use, and refrigerated water. In addition, highly performing heat exchangers ensure the air treatment and provide new air across the building.

9.4.2 Seismic Hazard

The aim of hazard analysis for a site is to estimate the rate of exceedance of a given ground motion intensity measure, i.e., that with a given annual probability of exceedance or average return period. The intensity measure traditionally used to represent the seismic hazard has been the peak ground acceleration (PGA), possibly associated with a spectral shape to immediately estimate a structure acceleration.

Once made clear that displacements are more relevant than accelerations, it may appear rational to shift to a displacement response spectrum as key intensity

measure. Someone may state that there is no difference, since displacement spectrum ordinates (S_{Δ}) can be derived from pseudo-acceleration spectrum ordinates (S_A) as a function of the period of vibration (T): $S_{\Delta}(T) = (T/2\pi)^2 S_A(T)$. This is a misleading observation, since peak displacement and corner period are essentially affected by the long-period part of the acceleration spectrum, where accelerations are low and consequently little attention is paid (Calvi 2013).

The discussion becomes more complex when the problem to be addressed is how to define the seismic intensity parameter based on seismic sources and their assessed potential to induce given magnitude earthquakes with specific recurrence intervals. The standard approach is a site-specific *probabilistic seismic hazard analysis* (PSHA), based on the separate consideration of all possible earthquakes that could occur within a given region, their frequency of occurrence, and the levels of ground motion intensity they could produce at a given site.

For the purpose of this exercise, the outcome of the FP7 European project SHARE (Giardini et al. 2013) has been utilized for the implementation of the corresponding PSHA model, which has been used for the computation of uniform hazard spectra for the locations referred in Sect. 9.4.1. To this end, it should be mentioned that due to the lack of publicly available information regarding seismic hazard results for Armenian territory (to the authors' knowledge), Yerevan and Istanbul are hereby considered identical for seismic analysis purposes.

9.4.3 Energy Demand

The most commonly used methodology for the definition of energy demand is stationary and based on heating degree days. Heating degree day (HDD) is a measurement designed to reflect the demand for energy needed to heat a building and is defined as a measure of the coldness of the weather experienced. A day's average temperature gives some idea of how much energy will be required on that day for heating purposes. The calculation procedure assumes some energy will be required on any day that has an average outdoor temperature of less than 18 °C (65 °F), computing the heating needs for each day by subtracting the day's average temperature from 18 °C. The result is the number of heating degrees for that day or HDDs.

The energy demand for cooling, which varies significantly as a function of the climatic region and building use, has also been taken into account in all the case studies presented in Sect. 9.4.1. In extreme cases such as healthcare facilities, the cooling demand can indeed be very high in the summer period and possibly necessary even in the winter season. On the other hand, school buildings are usually associated with low or negligible cooling demands, given the fact that building use is interrupted in the summer period.

Italy is divided in six climatic zones from A to F, as shown in Fig. 9.12, based on the values of degree days. The Italian code, such as the majority of the European

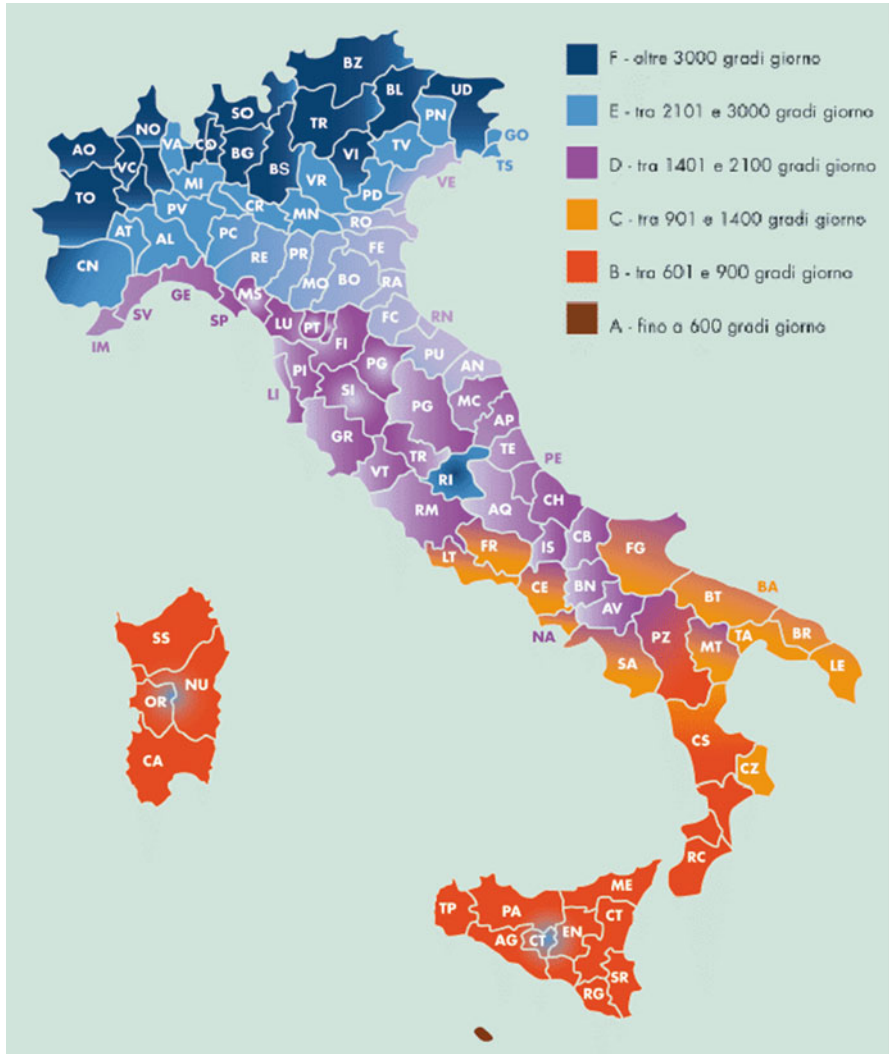


Fig. 9.12 Italian climatic zones, referred to degree day units

codes, defines both the climatic zone and the time interval in which heating system can be used, in order to reduce energy consumption.

According to the above, it is clear how benchmarking energy use can provide a mechanism for measuring how efficiently a building uses energy in relation to other similar buildings or modeled simulations of a building built to code or desired standard. Benchmarking models developed from energy efficiency indicators are valuable tools for both the government and the private sector in managing energy consumption. Some governments have used these tools to formulate policies for

the efficient use of energy in buildings (Chung et al. 2006). Hence, it is clear that by making energy performance information readily available, disclosure of such ratings can facilitate market transformation toward more energy-efficient buildings.

Climatic data and energy demand definition for the locations of Istanbul and Yerevan have been established according to the definition provided by the Casanova software (CASAnova 3.3—an educational software for heating and cooling energy demand as well as the temperature behavior of buildings: http://nesal.uni-siegen.de/index.htm/?softlab/casanova_e.htm), developed by the University of Siegen, Germany.

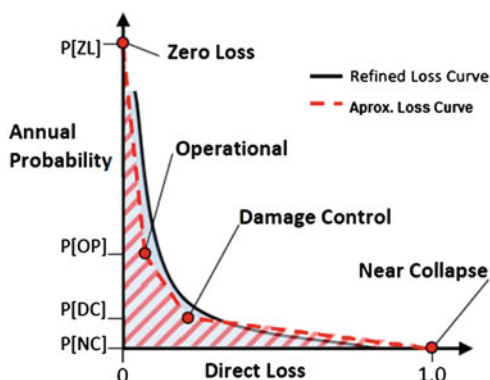
9.4.4 Seismic Resilient Assessment

According to Mitrani-Reiser (2007), a loss estimate could be performed considering each component-based fragility function and assuming a replacement cost equal to the total repair cost of all damageable components considered. A more complex approach has been proposed by Ramirez and Miranda (2009), whereby the component inventory is still associated to damage fragility functions, but these are associated to a probability of exceedance and to a probability of implying a repair cost level, according to a scheme developed at the Pacific Earthquake Engineering Research Center (PEER, see Haselton et al. 2007).

It is interesting to note that the application of the two aforementioned methods to the same sample reinforced concrete frame building, designed conforming to the applicable codes, resulted in the prediction of expected annual losses equal to 0.55 % and 0.9 % of the replacement cost, respectively. In this context, a simplified approach based on direct displacement-based assessment concepts, developed with the aim of making it more applicable in the common practice (Sullivan and Calvi 2011; Welch et al. 2012), is adopted in this document.

According to the works of Calvi (2013), Sullivan and Calvi (2011), and Welch et al. (2012), as presented in Fig. 9.13, a building-specific *loss exceedance curve* can

Fig. 9.13 Schematic representation of simplified building loss curve (from Welch et al. 2012)



be approximated by a simplified *loss exceedance curve* defined by four points that represent the annual probability of exceedance of particular damage states.

These damage states can adequately represent the building behavior, which is intuitively apprehended by the fact that lower *loss* ratios, usually related to operational damage states (building is considered fully or nearly fully operational), are related to lower seismic intensities, which have a higher probability of being exceeded, and a more severe damage state is expected to be related to both higher *loss* ratio and lower annual probability. Hence, by defining the annual probability of exceedance and *loss* ratios associated with the referred damage states (zero loss, operational, damage control, and collapse, as presented in Fig. 9.13), it is possible to completely compute the loss exceedance curve of a particular building, subjected to a given site seismic hazard.

The definition of the aforementioned damage states requires a relatively extensive discussion and will not be presently addressed for the sake of synthesis, referring the reader to the aforementioned publications. However, different retrofit techniques will influence the building performance at different damage states. Accordingly, given the fact that the *expected annual loss* is given by the area of the *loss curve* (Fig. 9.13), improving the building performance to less severe performance objectives (such as “operational” and “damage control”), therefore reducing its annual probability of being exceeded, will have a significantly greater impact in the final value of *expected annual loss* than the prevention of collapse or near collapse.

In the aforementioned framework, the objective of loss analysis is to calculate the probable repair cost for each level of damage state defined above. In principle, a loss estimate should include death toll, repair cost, and downtime consequences (the well-known *3D approach*; see Fajfar and Krawinkler 2004). However, one chooses to neglect the value of human life in the appraisal of seismic-induced *losses*. To this end, the seismic *loss* can strictly be evaluated in terms of the ratio of *cost to repair* to *cost to rebuild*, to which the associated indirect (downtime) *losses* are appended. For the sake of simplification, indirect (or downtime) *losses* are not considered in the present exercise.

Similarly to what has been performed in the work of Calvi (2013), for each assessed building and specified location, site seismicity has been assessed, and a complete adaptive pushover analysis has been run. For each damage state and corresponding return period, drift and floor acceleration have been computed (as average values), considering each floor, and the corresponding damage has been calculated. In its extreme simplification, one can assume that the cost of repair will be proportional to damage, for example, associating 75% of the value of the building to nonstructural content and 25% to structures, as proposed by Calvi (2013). The nonstructural part has been considered 80% drift sensitive and 20% acceleration sensitive, and each story has been assumed of equal value. Furthermore, assumptions on floor acceleration-associated and drift-associated nonstructural damage fragility, as well as drift-associated structural damage fragility, shall be referred to the work of Calvi (2013), as illustrated in Fig. 9.14.

Again, this can be modified and elaborated, and probabilistic aspects can be included without losing generality. In this framework, however, the attention will

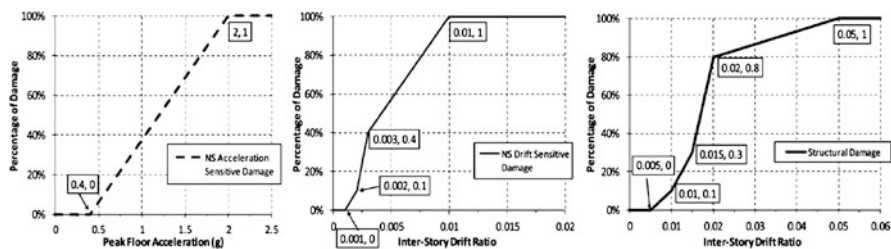


Fig. 9.14 Assumptions on floor acceleration-associated nonstructural damage (*left*, weight 20%), drift-associated nonstructural damage (*center*, weight 80%), and drift-associated structural damage (*right*), from Calvi (2013)

be focused on cost of different strengthening measures and on their comparison with a reduction in the expected repair costs, to obtain some cost-benefit evaluation to drive the strengthening choices.

9.4.4.1 Implemented Improvements

The subject of selecting the appropriate technical solution lies on the evaluation of the available techniques and its repercussion in a particular feature of building performance, as well as social, economic, and historical environment. As stated by Thermou and Elnashai (2006), the selection of the rehabilitation scheme and the level of intervention are a rather complex procedure, due to the fact that many aspects of different nature come into play when deciding which strategy to employ.

As supported by Calvi (2013), the possible alternative choices to be considered are schematically subdivided into three conceptual categories: the modification of damage and collapse modes (Elnashai and Pinho 1998; Thermou et al. 2007), the introduction of isolation systems (Filiatrault and Christopoulos 2006), and the reduction of the displacement demand by added damping or tuned masses (Sadek et al. 1997). In this context, this section provides a brief overview of the strengthening measures considered in this exercise (see Sect. 9.5), highlighting its relative effects, with no attempt to depict a complete and thorough presentation, impossible within the space constrains of an article:

- *Strengthening elements* (“retrofit 1”): A basic strategy to improve the seismic response of a building counts on the application of capacity design principles to eliminate all possible sources of brittle failures. In this context it is thus possibly required to increase some element strength in a selected way, to favor ductile damage modes. For example, it is typical to increase the shear strength of columns and beams to obtain flexural failure modes, to increase the strength of external joints, and to increase the flexural strength of columns to shift the formation of plastic hinges to the beams. This last example does not aim to avoid a brittle collapse, but to prevent the formation of a soft story. In some

case (possibly academic), weakening ductile modes have been considered instead of strengthening brittle ones. These kinds of intervention tend to modify in a significant way the last part of the pushover curve (and possibly the associated vertical deflected shape), increasing the displacement capacity of the structure, but may have a negligible effect on the first part of the curve (the modification of stiffness up to yielding is not significantly affected) and on the yield strength (since, in general, shear and flexural failure modes have similar strengths). Typical interventions are based on an external jacketing or wrapping of an element or part of it, using carbon or glass fibers, steel plates, or thin layers of reinforced concrete. It is obvious that the cost of strengthening of an element will vary significantly, as a function of its geometry and of the applied technique; therefore, estimates provided by Calvi (2013) are presently considered.

- *Locally increasing the deformation capacity* (“retrofit 2”): If it is assumed that all the possible brittle failure modes have been eliminated by a proper application of capacity design principles, i.e., by an appropriately selected local element strengthening, the displacement capacity of the structure can be limited by insufficient curvature (and consequently rotation) capacity in critical section of columns and beams. An insufficient rotation capacity of columns can only be detected in the case of a soft story formation or exclusively at the column base. Note that a soft story mechanism is not always unacceptable; it depends on the associated story rotation capacity (including second-order effects) and the associated global displacement capacity (Calvi 2013). These kinds of intervention are normally based on confining measures, to avoid bar bucking and increase the compression deformation capacity of concrete. Fiber wrapping and steel encasing are thus again the typical choices, which can, however, be limited to the critical zones of the elements. The effects on strength and stiffness will be even more negligible than in the previous case, and the effects will be still limited to the last part of the pushover curve. The cost per structural member is therefore lower, but of the same order of magnitude, of that discussed at the previous point (Calvi 2013). In the discussion of relative merits of different strengthening choices, no distinction will be made about these two kinds of strengthening for what concerns costs.
- *Inserting additional elements* (“retrofit 3”): A conceptually different approach to seismic strengthening relies on the insertion of additional elements reacting to horizontal actions. This is normally based on steel-braced frames or concrete walls (possibly obtained by strengthening masonry panels) that could be inserted in the interior of a building or outside it. If the primary reaction system of the original building was already made by walls, the purpose could be to increase strength and stiffness and to regularize the torsional response, thus reducing the expected damage even at relatively low displacement demand. If the original structural system was based on frames, the introduction of much stiffer elements may completely change the response, arriving at the limit that the original frame can give a negligible contribution to the response, and the only fundamental requirement will be that its displacement capacity will be larger than the displacement demand associated with the response of the new shear wall

system (Calvi 2013). In all cases two issues will have to be carefully considered: the capacity of the foundations corresponding to the new shear walls and the capacity of the horizontal diaphragm to transmit the action, globally and locally. To estimate the potential average cost of this kind of intervention, the approach proposed by Calvi (2013) will be assumed.

- *Capacity protection of existing structure* (“retrofit 4”): The insertion of an isolation system, at the base or at some height of the building, can often be a last-recourse intervention to improve the seismic performance of the building. The essence is that in this way the maximum shear that will pass through the system is governed by the system capacity (see, as a general reference, Filiatrault and Christopoulos 2006). As an example, imagine using friction pendulum devices: the maximum shear is essentially governed by the stick-slip value, which is typically in the range of two times the dynamic friction (Calvi et al. 2010). Using devices with a dynamic friction in the range of 3–5 %, it is likely that the maximum base shear force on the building will be in the range of 6–10 % of gravity. For earthquake events, or portions of events, that will not induce this level of acceleration, the structure is responding like a fixed base structure, while for any value of acceleration exceeding this value, the difference in base shear, and consequently in structural drift demand, will be marginal (Calvi 2013).

In general, the global cost is proportional to the plan area of the building, rather than to its volume, and may be as high as about 1200 EUR/m² for the most complex cases, including uplifting (Calvi 2013):

- *Introducing tuned masses* (“retrofit 5”): An example of intervention oriented to the reduction of demand is the introduction of a tuned mass. The general concept is simple: if the building can be regarded essentially as a single degree of freedom system, with most of its mass associated to the first mode of vibration, adding a tuned mass that vibrates with a similar period of vibration, but in the opposite phase, will induce a favorable reduction of shear force at all instants (Calvi 2013). This applies when the system responds essentially elastically. A complete description of the approach for seismic application is obviously more complex, and it can be shown that the maximum efficacy can be obtained for a specific ratio ($f = T_S/T_{TM}$) between the first period of vibration of the building (T_S) and the period of vibration of the tuned mass (T_{TM}) (see Sadek et al. 1997).

Again, it is difficult to give reliable figures of cost; however, as proposed by Calvi (2013), a rough estimate of a mean cost may be around 15 EUR per cubic meter of building.

For each one of the five strengthening strategies, a pushover curve has been recalculated, obtaining the following effects (Calvi 2013):

- For the case of member strengthening, the curve does not vary in the first part, but larger displacement capacity is achieved.
- Adding a shear wall system increases the shear capacity significantly, reducing the displacement capacity.

- Inserting a base isolation system does not induce changes in the first part of the curve, but the limitation of base shear avoids brittle failure modes.
- The additional damping case is not featured in this step, since its effect is considered on the demand side, reducing it, rather than modifying its capacity.

9.4.5 Energy Efficiency Assessment

The directive on the energy performance of buildings (EPBD) of the European Parliament and Council on energy efficiency of buildings came into force on 4 January 2003 and was deemed to be implemented by the EU member states by late 2006. Inspired by the [Kyoto protocol](#), this directive forced every member state to meet minimum requirements in terms of energy efficiency both in the new constructions and in the renewal of any building. In reality, different approaches are currently used in European state members to encourage energy efficiency in building codes for new buildings and major renovation or refurbishment. Most of them are based on energy efficiency indicators, which are basically used to establish the energy consumption performance level of energy-consuming systems.

The importance of the external climate is tremendous when it comes to energy efficiency decisions; in fact the different climatic zones in which a building will be considered to be located strongly influence not only the choices related to the energy system but also the strategic selection of the most appropriate solution to enhance the building's overall energy performance. The Italian classifications actually used to label the existing and new buildings do not yet take into account the energy consumption due to water supply and to cooling systems, since cooling is not compulsory except in healthcare facilities. However, the Italian code requires that 55% of the total energy for water heating shall be supplied by means of renewable energies (such as solar panels or heat pump) (D.P.R. 2009).

Notwithstanding the above, the UNITS (2008b, 2012) based on the law requirements of the European Union in terms of energy efficiency establishes a simplified method to calculate a ratio for water and cooling consumption, which has been used in this work in order to estimate the overall amount of consumed energy, allowing a more realistic result in terms of return period of the initial investment. The energy needed for cooling is strictly related to the use of the building, its location, and the decision-makers' motivation to invest. To this end, it is considered reasonable that in temperate climates, primary and secondary schools are not equipped with air conditioning systems, since the warmest period corresponds with the inactivity period of the school itself.

Similarly to that presented in the previous section for the earthquake resilience assessment, since the expected annual *loss* in energy efficiency terms is determined according to an analog ratio, cost-benefit analysis can likewise be performed, being expressed in terms of the correspondent break-even point for different solutions.

9.4.5.1 Implemented Improvements

According to the directive on the energy performance of buildings, enhancing the energy efficiency of building means to provide substantial improvement measures both on the envelope of the building and HVAC system, which are responsible for the indoor climatic conditions, as dictated by the so-called building-plant system. In this context, the referred envelope can be acknowledged as the “skin” of the building, since it works as the interface between the interior and the outdoor environment (including walls, roof, and foundation). By acting as a thermal barrier, the building envelope plays an important role in regulating interior temperatures and strongly contributes in determining the amount of energy required to maintain thermal comfort. Minimizing heat transfer through the building envelope is undoubtedly crucial for reducing the need for heating and cooling (C2EF 2012).

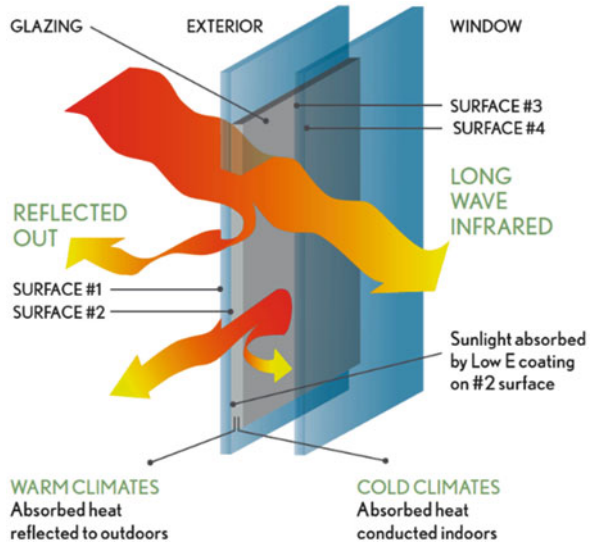
Different intervention can be done while retrofitting the buildings, by using architectural and heating/cooling solutions to reduce energy losses. Usually, an energy analysis of the existing building must be done in order to point out the weaknesses of the overall energy performance. The results of a careful energy diagnosis are of great help in determining the most effective solution to be used. Local climate is, of course, an important determinant for identifying the design features that will result in the greatest reductions of energy needs. These may include such measures as south-facing windows in cool climates and shading to avoid summer sun in hot climate. The use of very high-performance doors and windows is one of the principal goals to achieve, in order to increase the general performance of the buildings, in general both in new and retrofit construction.

It is clear that the *fenestration* (which includes windows, exterior doors, and skylights) influences both the lighting and the HVAC requirements of a building. In addition to design considerations (the placement of windows and skylights affects the amount of available natural light), materials and installation can affect the amount of energy transmitted through the windows, doors, or skylight, as well as the amount of air leakage around the window components. Thus, new materials, coatings, and designs contribute to improved energy efficiency of high-performing windows, doors, and buildings (DOE 2006).

Some of the energy performance advances based in windows include multiple glazing, the use of two or more layers of glass or other films for insulation, which can be further improved by filling the space between the panes with a low-conductivity gas, such as argon, and low-emissivity (low-e) coatings, which reduce the flow of infrared energy from the building to the environment. Shading, shutters, and reflection can also greatly reduce sun penetration of windows and other glass areas, as schematically presented in Fig. 9.15.

In residential buildings, using optimum window design and glazing specifications is estimated to reduce energy consumption from 10 to 50 % below accepted practice in most climates. Moreover, in commercial buildings, an estimated 10–40 % reduction in lighting and HVAC costs is attainable through improved fenestration (Arvizu 2011).

Fig. 9.15 Schematic representation of insulated glass solution



Another fundamental issue in design and retrofitting stages is the enhancement of buildings' insulation, due to the provided resistance to heat flow, reduction in the amount of energy needed to sustain the interior desired temperature in the winter and summer. A variety of insulation options exist, including blanket, concrete block, insulating concrete forms, spray foam, rigid foam, and natural fiber insulation. Usually insulation is discussed in terms of its ability to resist heat flow, which depends on the R -value which is a measure of thermal resistance of the material and is the mathematical inverse of the U value (**overall heat transfer coefficient** that describes how well a building element conducts heat). The higher is the R -value of an element, the better is the insulation of the element itself. Adding insulation strategically will improve the efficiency of the building; however, it is only effective if the building is properly sealed. Sealing cracks and leaks prevents air flow and is crucial for effective building envelope insulation. Leaks can generally be sealed with caulk, spray foam, or weather stripping (C2EF 2012).

Another important way to provide high level of efficiency is to focus on the roof design and materials. This can drastically reduce the amount of air conditioning required in hot climates by increasing the amount of solar heat that is reflected, rather than absorbed, by the roof. High-performing roofs are estimated to reduce the demand for peak cooling by 10–15 % (Arvizu 2011). In addition to the reduction of consumption, the roof can offer several opportunities for installing on-site generation systems that use renewable energy (solar, photovoltaic, etc.). In addition, it may include supplementary layers such as a **root barrier** and **drainage** or **irrigation** systems, which enhance the rainwater absorbing properties (<http://en.wikipedia.org/wiki/Rainwater>); provides better **insulation** (meaning an effective reduction for energy costs); minimizes the acoustic impact; helps in maintaining the waterproof of the ceiling; and gives a contribute to lower urban air temperatures (C2EF 2012).

In strict analogy with the roof, the amount of energy lost or retained through walls is influenced by both design and materials. Design considerations affect clearly the placement of windows and doors and the size and location of which can be optimized to reduce energy losses, while the use of the appropriate material can be more complicated, since both material selection and wall insulation affect the building's thermal properties. There are several different solutions that can be used in order to obtain virtuous results in the energy efficiency of the envelope, if they are to be applied during the design phase. This can be obtained based also in the thermal mass of the construction material (Levy et al. 2003). Thermal mass materials include traditional materials such as stone and adobe and cutting-edge products, such as those that incorporate phase change materials (PCMs). PCMs are solid at room temperature and liquefy as they absorb heat; the absorption and release of energy through PCMs help to moderate building temperature throughout the day.

Energy retrofitting of buildings is more difficult, given the massive measures required to obtain a well-performing building envelope. Therefore, in order to avoid severe workloads, one of the main used strategies is to cover up the entire building with insulating panels (coated structures) and substitute the fenestration with new improved frames in order to reduce the fuel consumption. Together with the envelope, a great importance must be given to the air conditioning and heating systems. It is shown that heating, ventilating, and air conditioning (HVAC—heat ventilation and air conditioning systems) account for 39 % of the energy used in commercial buildings. It is clear that by improving the control of HVAC operations and the efficiency of machines, significant savings can be achieved. The use of high-performance HVAC equipment can result in considerable energy, emissions, and cost savings (10–40 %) (Arvizu 2011).

Buildings constructed for healthcare purposes are well known for being particularly “energy consuming,” particularly due to the high standard of IAQ (indoor air quality) established in local codes. The recent Commercial Buildings Energy Consumption Survey (CBECS) conducted by the Energy Information Administration (EIA) shows that the average hospital in North America consumes nearly 250 % more energy than the average commercial building (ASHRAE 2011a). In an average hospital, for example, lighting consumes a large portion of the overall energy budget. Therefore, the design should include an energy-efficient lighting design and efficient lighting fixtures as well as evaluating opportunities for dimming controls and multilevel switching systems. In the many areas where the design team brings quality daylight into the space, lighting controls can be used to regulate the output of electric lights to optimize the quality of the visual environment, while saving significant amounts of energy. Many different measures and design solutions can be employed in order to achieve goals of consumption reduction in this kind of facilities, as, for example, *photovoltaic technology*, *cogeneration* (cogeneration heat and power—CHP systems) to simultaneously generate **electricity** and **useful heat**, geothermal heat pump (GHP) from earth's natural heat to provide heating and cooling and water heating, and solar panels for heating water and other purposes, such as “renewable energy.”

The use of a suitable and well-designed air conditioning system plays also a very important role. Solutions such as VAV (volume air variable), low-temperature radiant systems, and free cooling and free heating solutions based on the indoor quality of the air can lead to significant savings with no relevant up-front investments (ASHRAE 2011b). Furthermore, using new energy-efficient lighting, such as LED and occupancy sensors to avoid the waste of lighting when there is an absence of people together with lighting control systems with photo sensors which determine the lighting levels and dimmer lights to meet the minimum required level, will also provide a great improvement to the final bill in all kinds of buildings, with exception of residential dwellings, in which energy consumption due to lighting is relevant (ASHRAE 2011c).

9.5 Seismic Resilience and Energy Efficiency: Results and Conclusions

9.5.1 Result Integration and Comparison

In order to evaluate the influence of different measures for building retrofit and/or energy efficiency improvement, as well as the more general impact of improving the *green* and *resilient* components of *GRI*, a cost-benefit analysis is proposed.

The *benefit-cost* ratio at a given time over the building life cycle is expressed by the ratio between (a) the economic benefit determined by the difference between *net present value* (NPV) of accumulated *loss—expected annual loss (EAL)*—for the initial and improved states and (b) the cost associated with the referred improvement:

$$\frac{\text{Benefit}}{\text{Cost}} = \frac{\text{NPV}_{\text{Existing}} - \text{NPV}_{\text{Retrofit}}}{\text{Cost}_{\text{Retrofit}}}$$

The *net present value* (NPV) of a given value of *loss* for a specific time is intended to account for the interest rate—*r*—one would expect to pay if capital was borrowed from others or the rate of return on investment that would be expected (Calvi 2013), as follows:

$$\text{NPV} = \frac{\text{Value}}{(1 + r)^t}$$

At this stage, for simplicity purposes, it is decided not to explicitly consider the influence of the interest rate in the NPV calculations (i.e., *r* equal to zero), when incorporating the results of both approaches. Although the latter can be considered as a drawback of the present exercise, it is considered as a suitable assumption, since the main objective is the validation of the main guidelines for a more extensive exercise.

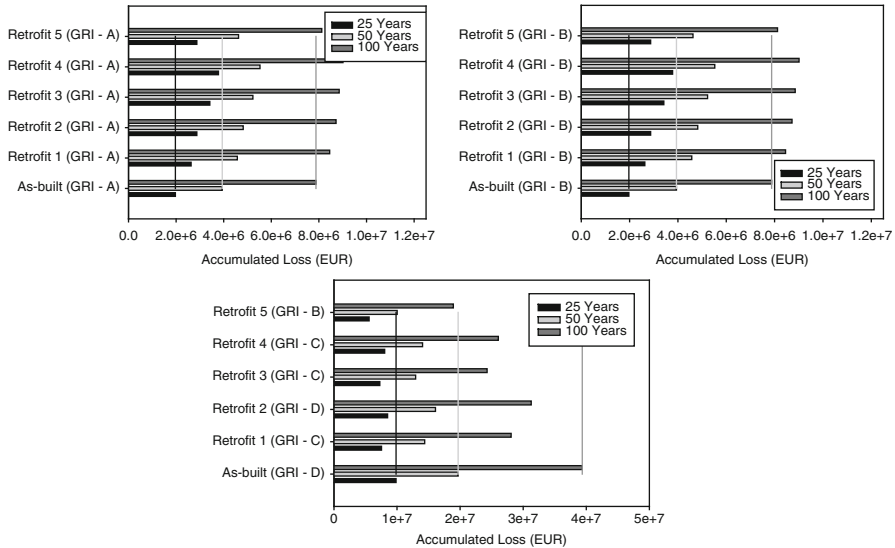


Fig. 9.16 Earthquake resilience assessment results. Building A: design location—Pavia (*upper left*), Messina (*upper right*), and Istanbul/Yerevan (*bottom*)

According to the above, the referred financial benefit indicators can be combined in order to determine the time at which the return of the initial investment will be achieved—the *break-even point*—for a particular building and intervention, in which detailed information regarding the analytical procedure is provided:

$$t_{\text{break}\times\text{even}} = \frac{\text{Cost}_{\text{ratio}}}{\text{EAL}_{\text{INITIAL}} \text{EAL}_{\text{IMPROVED}}}$$

$\text{Cost}_{\text{ratio}}$ stands for the cost to improve the building behavior for seismic resilience or energy efficiency, divided by the total building value.

9.5.2 Seismic Resilience and Energy Efficiency Assessment

For what concerns the evaluation of energy efficiency and seismic resilience assessments, it shall be mentioned that the results are gathered in a graphical fashion, for comparison purposes, according to the results of accumulated *loss* at periods of 25, 50, and 100 years, as depicted in Figs. 9.16, 9.17, 9.18, 9.19, and 9.20.

Figures 9.16, 9.17, 9.18, and 9.19—referring to case studies A, B, and C, respectively—illustrate the accumulated seismic *loss* resulting from the integration of EAL_S over periods of 25, 50, and 100 years, in which the results from an “as-built” situation are directly compared with the outcome of retrofit strategies 1–5 presented in Sect. 9.4.4.1.

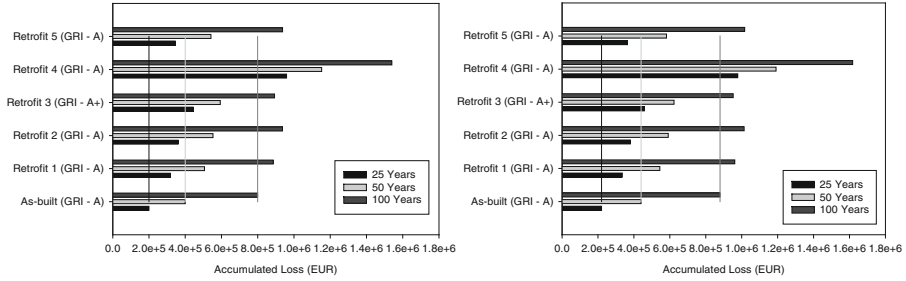


Fig. 9.17 Earthquake resilience assessment results. Building B: design location—Emilia-Romagna (*left*) and Messina (*right*)

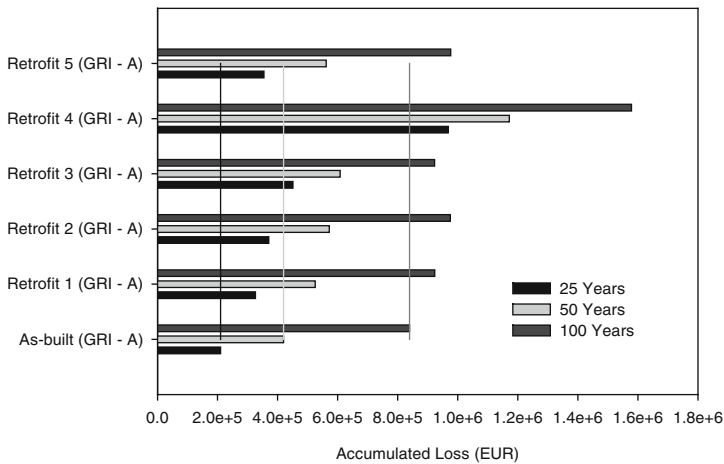


Fig. 9.18 Earthquake resilience assessment results. Building B: Istanbul/Yerevan

Similarly, energy *loss* accumulated over the aforementioned periods is depicted in Fig. 9.20, where the results referring to an “as-built” configuration are illustrated against the outcome of the enhanced situation for all the foreseen design locations (see Sect. 9.4.1).

9.5.3 Integrated Approach

For the purposes of integrated approach assessment, the most effective seismic retrofit scenario (see Figs. 9.16, 9.17, 9.18, and 9.19) in terms of *benefit-cost ratio* is selected for each of the buildings and locations. Accordingly, as presented in Figs. 9.21, 9.22, and 9.23, *benefit-cost ratios* for periods of 25, 50, and 100 years are calculated for earthquake resilience and energy efficiency improvement situations, as well as for the combined intervention.

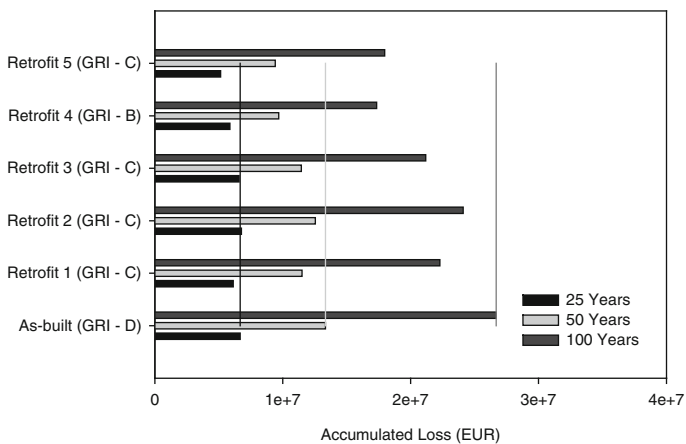
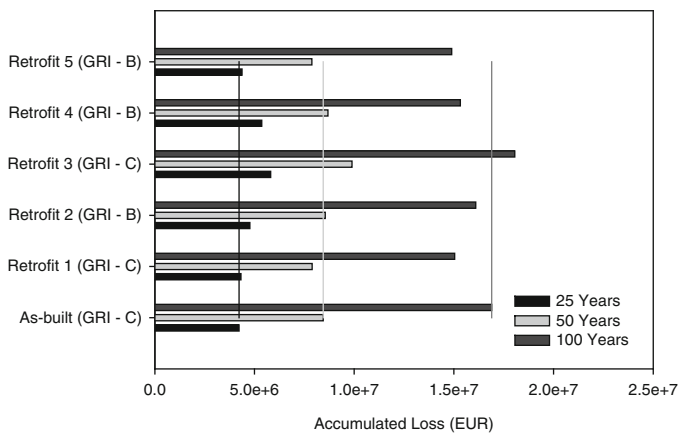
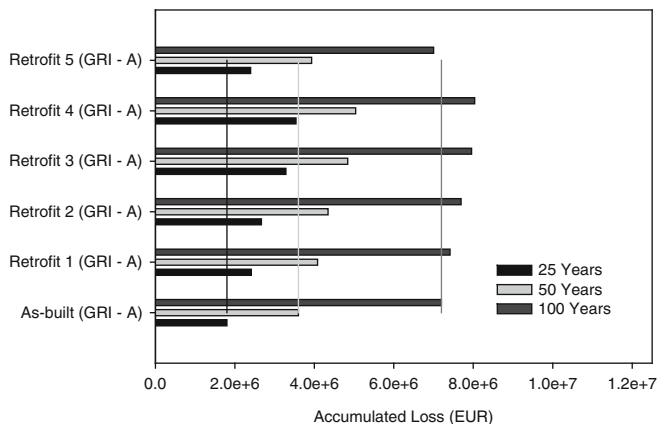


Fig. 9.19 Earthquake resilience assessment results. Building C: design location—Milan (*upper*), Messina (*middle*), and Istanbul/Yerevan (*bottom*)

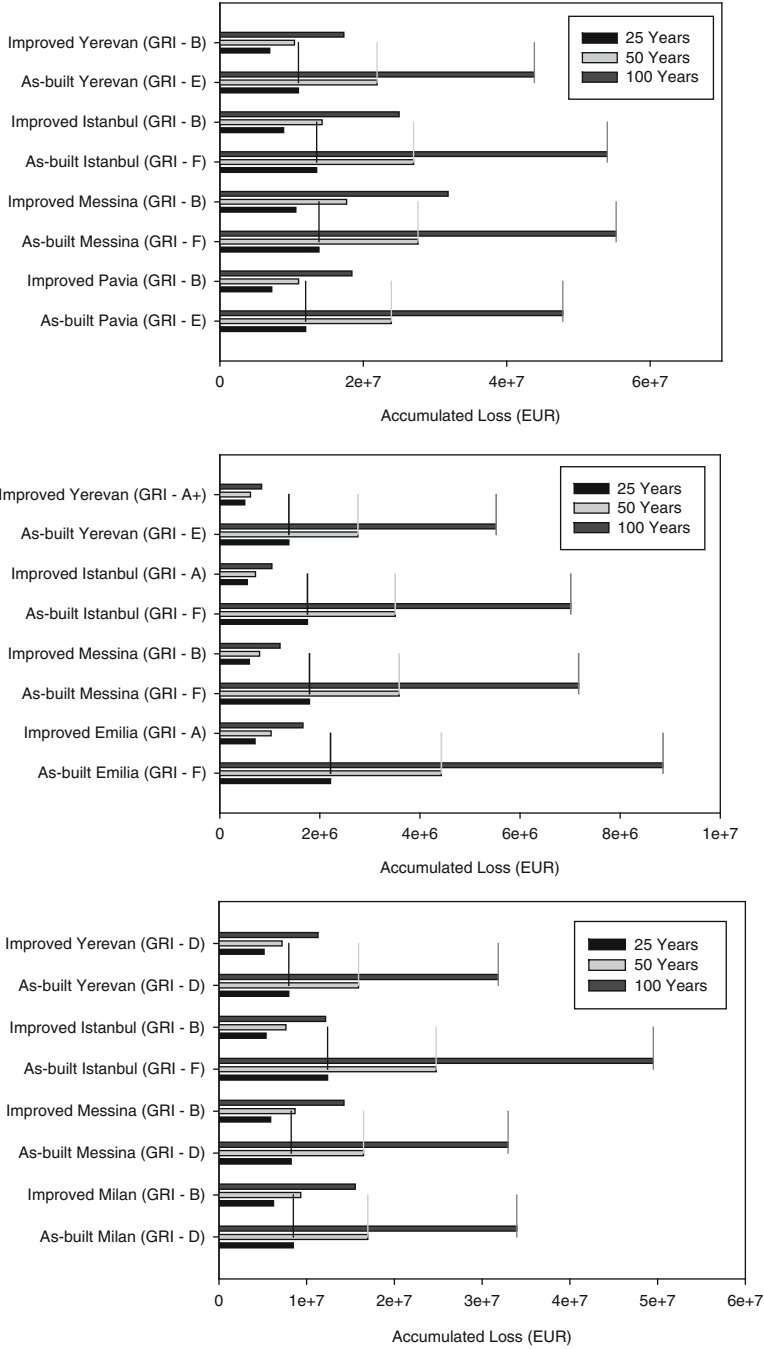


Fig. 9.20 Energy efficiency assessment results. Building A (*upper*), building B (*middle*), and building C (*bottom*)

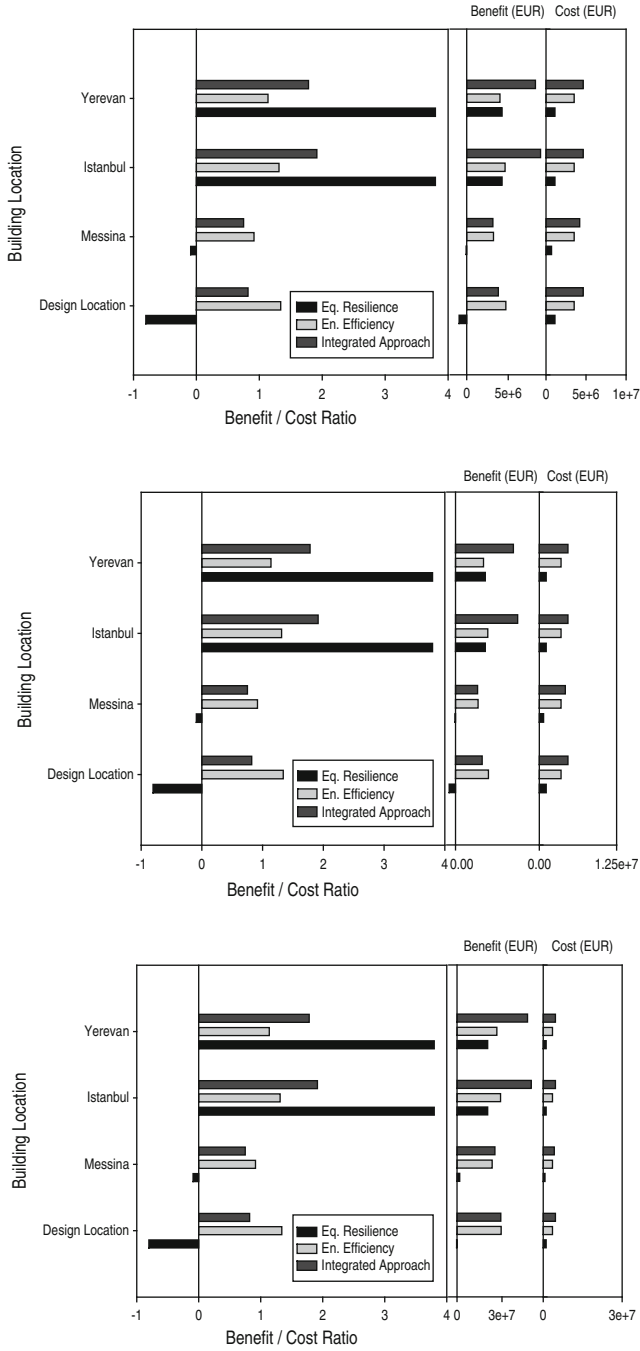


Fig. 9.21 Case study A—cost-benefit ratios for 25 (*upper*), 50 (*middle*), and 100 (*bottom*) years

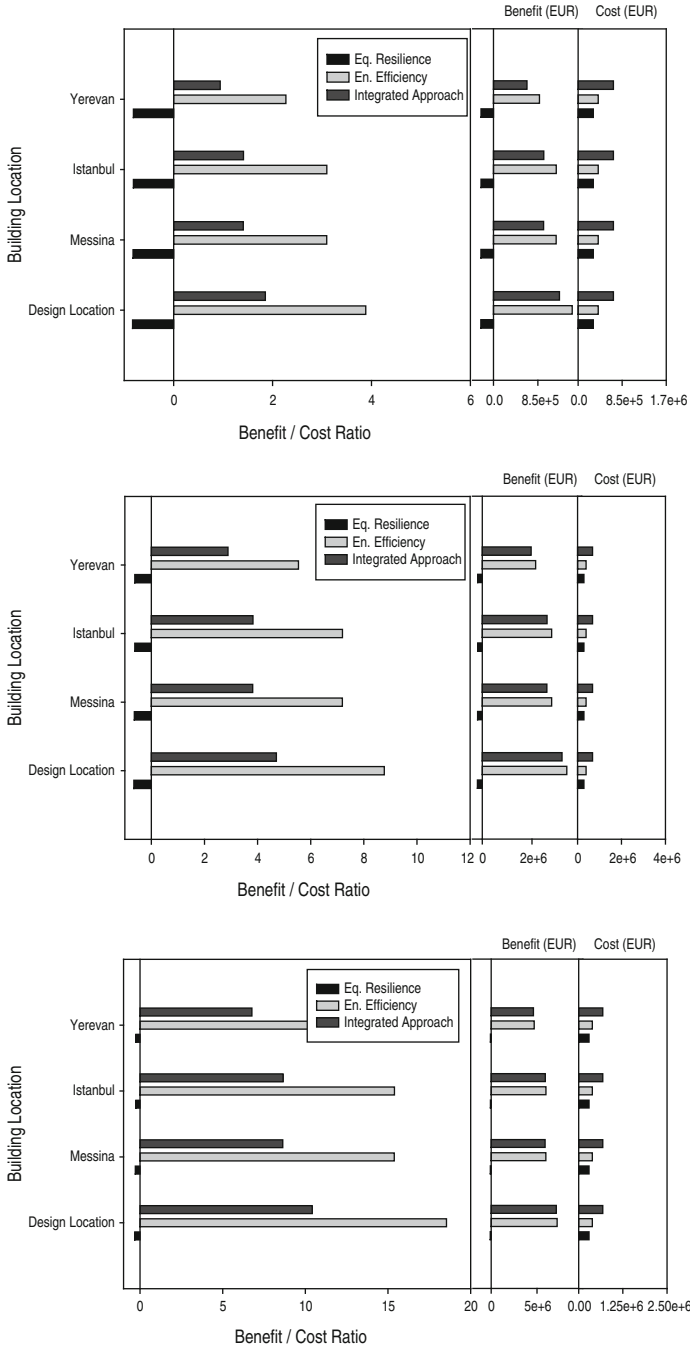


Fig. 9.22 Case study B—cost-benefit ratios for 25 (*upper*), 50 years (*middle*), and 100 (*bottom*) years

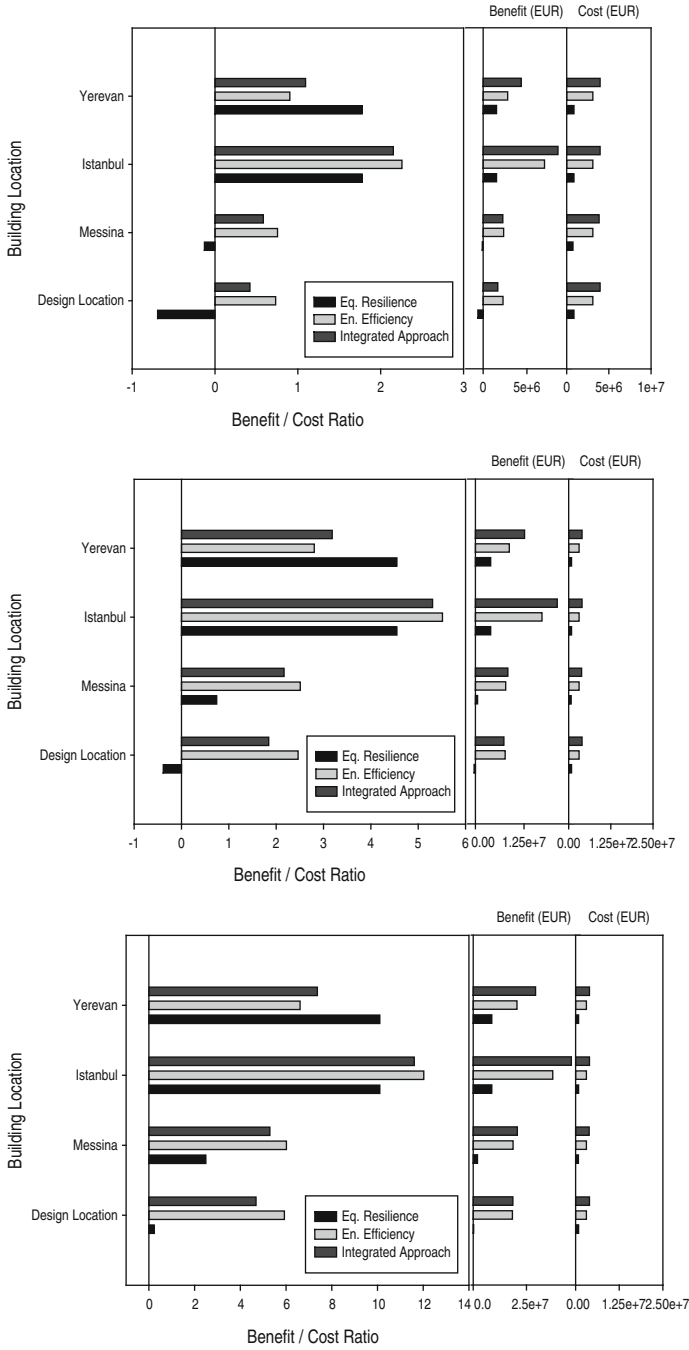


Fig. 9.23 Case study C—cost-benefit ratios for 25 (upper), 50 (middle), and 100 (bottom) years

As previously mentioned in this manuscript, the evaluation of the interest rate influence on the appraised results is not subject of detailed scrutiny. Thus, the subsequently presented results, which reflect a value of r equal to zero, are referred as the basis for the present comparison exercise. Moreover, as intuitively can be inferred, a negative *benefit-cost* ratio means in reality that at the time T (years) assessed, the reduction of *EAL* due to building behavior enhancement is not sufficient to compensate the initial investment required for the mentioned improvement (i.e., $T < \text{break-even point}$).

9.5.3.1 Conclusions

As presented in Figs. 9.20, 9.21, 9.22, and 9.23, addressing the matter of assessing the integrated advantages is not straightforward. As can be depicted in the mentioned figures, an analysis based on *benefit-cost* ratios cannot be dissociated from the correspondent absolute values of economic *benefit* and investment *cost*. To this regard, the following considerations can be gathered:

- As clearly illustrated in Fig. 9.20 (case study A), for the cases of Istanbul and Yerevan, significantly higher *benefit-cost* ratios can be attained for a particular intervention, even if similar values of economic *benefit* are presented for both approaches. In the case of building A, this is explained by the higher initial *cost* to improve the building from an energy efficiency point of view.
- Improving the behavior of a building with initial high *GRI* classification will likely lead to a very high investment return period, as expressed by the negative values of *benefit-cost* ratio determined for 25, 50, and 100 years for building B, as particularly evident in Figs. 9.21 and 9.22.
- The location of the building greatly influences the final result of the exercise in terms of both *resilience* and *energy* points of view. As illustrated in Figs. 9.20, 9.21, 9.22, and 9.23, for all the buildings analyzed, it is possible to depict a considerable trend of variation in *benefit* depending on the building considered construction site. This is related to the relationship between the demands at design and idealized locations, which essentially reflects the suitability of the design and retrofitted conditions to the expected demands. Thus, a building with poor *GRI* classification (not adequately designed), on either of the deemed approaches, will *a priori* attain greater benefit from a given improvement intervention than a building with high *GRI*.
- Distinct *energy* and *resilience benefit-cost* ratios for a given building/site configuration might be registered even for similar values of benefit, in cases in which the levels of initial investment differ significantly (see Fig. 9.20) or in situations in which considerable differences in benefit correspond to similar values of initial investment (see Fig. 9.21).

According to the aforementioned, it seems reasonable to assume a prioritization scheme in which the investment is directed to the maximum *benefit-cost* ratio (i.e., higher possible reduction of *EAL* for the minimum amount of initial cost).

To this end, the appraised results highlight the advantages of the considered *GRI* classification scheme, due to the fact that the higher *benefit-cost* ratio between seismic resilience and energy efficiency for a given integrated intervention tends to correspond to the approach with “poorer” *GRI* index (i.e., the one which can benefit more from a behavior improvement intervention).

The role of the idealized *GRI* classification should be appropriately emphasized under this context. Since the *GRI* classes are common for *green* and *resilient* indicators, it is not only possible to directly compare energy efficiency and seismic resilience from an *EAL* point of view, as it is plausible to assume that the *GRI*s of *green* and *resilient* approaches represent a proxy for investment return potential; i.e., “poorer” *GRI* classes are associated with higher potential for investment return and benefit maximization, as enunciated in the previous paragraph.

However, considering only one of the approaches (*resilience* or *energy*) might not be the most adequate solution, due to the fact that the *benefit* of a given intervention (*green* or *resilient*) can only be maximized up to the utmost possible level of building behavior improvement or, in other words, up to the point in which an additional investment does not result in *EAL* reduction, and therefore, the *benefit-cost* ratio is maximum. Thus, at least from a theoretical point of view, an integrated approach should always be advantageous with respect to the investment in only *earthquake resiliency* or *energy efficiency* improvement, dividing the investment in such a way that simultaneously maximizes the *benefit-cost* ratio of the “individual” improvements in *green* and *resilient* perspectives and its integrated result.

9.5.4 Future Developments

Under the previously mentioned context, a fully representative analysis campaign is submitted for further developments. According to the latter, all the applicable combinations of building configuration, retrofit and improvement techniques, seismic hazard and energy demands, as well as financial and economic parameters (such as interest rates and downtime *losses*) shall be convoluted in order to create a set of results that can adequately constitute the base for the development of integrated approach guidelines.

As presented in Sect. 9.2.3, recent efforts have been developed toward the explicit consideration of environmental impacts of earthquake action in a comprehensive approach. Thus, although only financial aspects are considered in the present exercise, an interesting further development would be the consideration of additional decision-making variables, directly related to the environmental counterpart of energy efficiency and earthquake *loss*, as well as the correlation between both.

In addition, it is required to identify possible challenges to be faced in the implementation of an integrated approach. They are expected to include mainly technical (related to the regional characteristic “know-how” and material/technical resources), bureaucratic (due to the possible necessity of institutional coordination between different decision-making agencies), and legislation issues (relative to the

applicability of different measures, under the context of regional code standards). However, the comprehensive compilation of such a set of constraints would require an extensive research procedure that cannot be performed in the present exercise and will, therefore, be recommended as the subject of further developments.

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