A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings

Bianchi, Simona; Ciurlanti, Jonathan; Overend, Mauro; Pampanin, Stefano

DOI
10.1016/j.engstruct.2022.114852

Publication date
2022

Document Version
Final published version

Published in
Engineering Structures

Engineering Structures 269 (2022) 114852

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings

Simona Bianchi [a,*], Jonathan Ciurlanti [b], Mauro Overend [a], Stefano Pampanin [b]

[a] Delft University of Technology, Julianalaan 134, 2628 BL, Delft, Netherlands
[b] Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy

ARTICLE INFO

Keywords:
Risk assessment
Probabilistic study
Seismic safety
Energy efficiency
Low-damage
Facades
Economic losses

ABSTRACT

Structural safety and environmental sustainability are major factors in investment decisions for building systems, but are rarely considered simultaneously. Recent research efforts have redressed this by developing assessment methodologies and technical solutions for integrated energy efficiency and seismic performance. These studies are typically limited to existing buildings and retrofit interventions at global building scale, whereas an effective framework could and should be part of the design process of either new or existing buildings at both building and component scales. This paper proposes a probabilistic-based assessment framework to assess the building performance in terms of integrated economic losses and support the selection of resilience-enhanced solutions. The proposed methodology is validated through its application to reinforced concrete case-study buildings consisting of traditional vs low-damage earthquake-resistant technologies coupled with energy efficiency strategies. Seismic and energy risk assessment analyses are performed accounting for both modelling uncertainties and earthquake/weather variability. Probabilistic distributions of the integrated economic losses are finally derived to compare the design solutions in terms of risk and reliability. The research outcomes demonstrate the effectiveness of the probabilistic approach for decision-making in building projects. Specifically, it is found that the economic losses can be highly underestimated (greater than40 %) in the single domains (energy or seismic); greater savings and return on investment can be achieved when the seismic safety is involved in the design process; probabilistic distributions and reliability/risk values can represent an effective tool to assess and compare design solutions.

1. Introduction

The construction sector has an obligation to mitigate the effects of climate change and its potential risks on society. The built environment currently accounts for 36 % of global final energy end-use and 37 % of energy-related carbon dioxide emissions [1]. This disproportionate impact on the environment is a result of the lack of public awareness of climate change in the past, as well as of inefficiencies in the design and operational stages of built artefacts (e.g. buildings, bridges, etc.). Sustainable development is essential for meeting the growing needs of the modern society, maintaining a livable climate and avoiding negative socio-economic impacts on future generations. The upgrade of existing building envelopes is estimated to lead to over 70 % annual CO_2 savings in 2050 from building stock in Europe [2]. The construction sector is therefore facing a challenging era in order to increase the environmental sustainability of our buildings and fulfill energy efficiency targets [3]. Although green financial incentives promoting the upgrade of building envelopes and the use of renewable sources and eco-friendly materials are attracting more interest and investments, environmental sustainability alone is insufficient to build a resource-efficient economy. In earthquake-prone countries, seismic risk reduction considerations need to be integrated into sustainable development strategies. Technical solutions combining damage mitigation measures with energy efficiency strategies represent an opportunity for higher return on building investment and larger economic savings [4]. It therefore follows that seismic safety and environmental sustainability should be considered simultaneously in both the design and rehabilitation process of buildings.

Lessons from past earthquakes (e.g., L'Aquila 2009, Christchurch 2011, Central Italy 2016) have repeatedly shown the vulnerability of existing buildings and further confirmed the severe impact of seismic events on the community. Post-earthquake damage, socio-economic

* Corresponding author.
E-mail addresses: S.Bianchi@tudelft.nl (S. Bianchi), jonathan.ciurlanti@uniroma1.it (J. Ciurlanti), M.Overend@tudelft.nl (M. Overend), stefano.pampanin@uniroma1.it (S. Pampanin).

https://doi.org/10.1016/j.engstruct.2022.114852
Received 19 February 2022; Received in revised form 9 August 2022; Accepted 17 August 2022
Available online 24 August 2022

losses and market disruption have highlighted the great mismatch between public expectations over the reality of seismic performance of modern buildings; targeting life-safety criteria is arguably not enough when dealing with new building construction [5]. Although modern buildings performed as expected by concentrating the inelastic demand in discrete plastic hinges zones as per capacity design principles, they were severely damaged after earthquakes and considered too expensive to be repaired, requiring demolition in many cases [6]. Furthermore, non-structural components (architectural elements, mechanical and electrical equipment and contents) generally provided the largest contribution to the post-earthquake economic losses, well exceeding the structural losses [7] and representing a percentage even greater than 70–80 % of the total building loss [8]. Due to their poor dynamic performance, non-structural components might lose functionality for low-intensity earthquakes and be seriously damaged or fail after moderate-to-high intensity earthquakes. Their damage can significantly affect the post-earthquake building functionality, contributing heavily to downtime and overall loss and representing a potential life-safety threat for occupants and pedestrians. As a result, seismic-risk awareness has increased among people, building owners and policy makers that are demanding for higher levels of earthquake protection for the overall building, including primary load-bearing structure and building envelope.

To enhance community resilience, both structural safety and environmental sustainability should be major concerns of decision makers. Although the need for integrated rehabilitation/retrofit strategies has emerged in recent years, there is still little consideration for the development of earthquake-proof and energy-efficient building systems in common practice. Yet, the technical complexity and invasiveness associated with the structural interventions currently discourage the implementation of an integrated strategy while the householders tend to opt for an eco-only intervention, thus impairing the potentially huge socio-economic benefits associated with the seismic risk reduction and not providing adequate seismic protection to the energy-efficiency investment. To provide evidence of the effectiveness of integrated designs/retrofits, the long-term value of combined technical solutions has been increasingly investigated in recent years and innovative multi-functional interventions have been proposed to enhance the performance of existing buildings and their envelopes [9–14]. Furthermore, research efforts have focused on the proposal and validation of multi-disciplinary assessment frameworks and practical tools to evaluate both the seismic safety and other performance aspects (particularly, environmental impact and cost-effectiveness) thus supporting the selection of optimal integrated designs [15–20].

The implementation of combined seismic and energy assessment and retrofit of existing buildings represents an important step change and a similar multi-performance integrated approach should be part of the design process of new buildings. Advanced multi-criteria performance-based approaches based on uncertainty propagation and computational optimization have been proposed to support the decision-making of new buildings [21–23], but none includes seismic performance and resilience indicators. To meet the societal demand for higher earthquake protection, the design should target high-performance, cost-effective and sustainable technologies capable of sustaining strong earthquakes with limited damage, minimum disruption of business and controllable socio-economic direct and indirect losses. A paradigm shift is needed toward damage-control design philosophies and building technologies consisting of advanced earthquake-resistant systems for both the primary structure and the building envelope [5,24]. Following this goal, innovative low-damage solutions have been investigated in recent years. For the primary load-bearing structure, in addition to, or complementary to and integrative of, more traditional technologies such as base isolation and dissipative braces, low-damage cost-affordable solutions based on post-tensioned rocking and dissipative mechanisms for either concrete (PREcast Seismic Structural System - PRESSS - [25,26]), timber (Prestressed Laminated timber - Pres-Lam - [27,28]) or steel [29,30] have attracted an increasing level of interest. Building on the same damage-control concept, innovative solutions have been proposed for both vertical (facades, partitions) and horizontal (ceilings) architectural elements and equipment. These systems rely upon connections detailed with relative movements between components and/or supplemental dissipation devices e.g., [31–34]. As a final step toward the development of resilient-enhanced buildings, all these low-damage solutions should be combined to create an overall high-performance building system. Initial cost/performance investigations on such (quasi-) earthquake-proof building systems have been carried out [35–37] and further studies are needed to standardize the connection detailing and, particularly, to integrate these low-damage solutions with energy efficiency techniques to target an “ultimate” high-performance sustainable building.

In order to support decision makers in the selection of advanced building systems, a comprehensive and robust procedure should be implemented to evaluate and compare the performance of possible design solutions for a new building project. Although risk assessment is currently adopted in earthquake engineering and probabilistic analyses for the calculation of the energy performance have emerged in the last years e.g., [38,39], an integrated fully-probabilistic risk assessment methodology has not been developed yet. Based on this consideration, this paper proposes a probabilistic-based framework to assess the integrated seismic and energy losses, by coupling seismic and energy simulations and accounting for both modelling uncertainties and earthquake/weather-related variability. Such a design approach produces more reliable outcomes by predicting - and thus targeting in the design phase - the probability of exceedance of a multi-performance (seismic and energy) building level, instead of relying upon single values of loss.

2. Integrated probabilistic-based framework

A probabilistic-based framework is proposed to assess the risks in building projects associated with the combined seismic and energy performance. An overview of the overall methodology is shown in Fig. 1. Alternative design configurations for the building as a whole, i.e. including primary structure, building envelope, equipment and contents, are first selected. Several sources of risk that might cause a variation in the building performance in terms of vulnerability/capacity (epistemic) and hazard/demand (aleatory) are considered for each design configuration. Although numerous sources of risk might be included, uncertain modelling parameters can be identified by referring to available sensitivity studies. Each uncertain input (materials, elements, design) is described by a probabilistic distribution, whose mathematical function is built based on literature data, manufacturer specifications or designers’ expert opinion. In addition to the epistemic uncertainty, the risk assessment analysis accounts for the aleatory variability in both seismic demand and weather conditions. By applying a sampling method (the Latin Hypercube Sampling [40] is selected for this specific study), values from these probabilistic distributions are retrieved to define a large number of scenario cases. Then, seismic and energy simulations are performed for each scenario and outcomes are collected in terms of seismic damage and energy consumption. To compare the single-domain (seismic or energy) and/or the combined performance, seismic and energy results are finally converted into direct economic losses, i.e. Expected Annual Losses (EAL_{S+E}), and curve-fitting techniques are employed to determine the probability distribution of the overall economic losses.

It is worth mentioning that this study employs a non-linear static approach for the seismic analysis. Non-linear static procedures are arguably the best compromise between accuracy and simplicity when compared to either simplified linear static, dynamic methods or more complex and time-consuming non-linear time-history analyses. Although non-linear static analysis can possibly lead to (slightly) conservative estimations of the economic losses [41], considering the

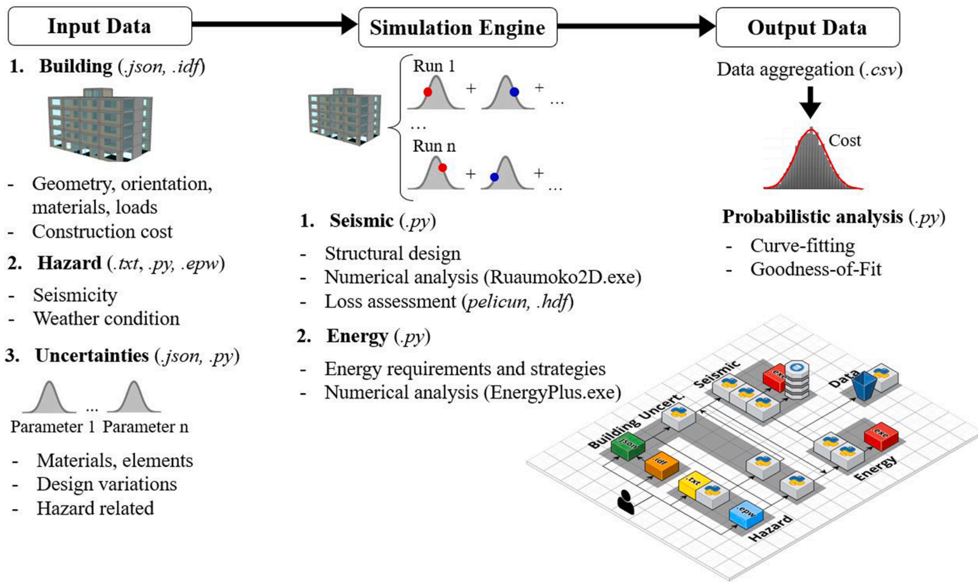

Fig. 1. Framework of the integrated probabilistic methodology.

complexity of the problem and its associated (epistemic and aleatoric) uncertainties, the method can represent a valid tool and more suitable approach for engineering practice to support the decision-making at early stage design of buildings, where the goal is to select the best alternative among design solutions (based on relative comparison, rather than absolute estimations).

A Python-based workflow is developed to automate the simulation process and manipulate large datasets. This consists of different modules (*Building*, *Hazard*, *Uncertainties*, *Seismic*, *Energy*) and sub-modules (e.g. *Seismic: Building design, Connection design, Modelling, Seismic Analysis, Loss assessment*) working as standalone or within a series of automated routines. The modules are self-contained scripts developed in Python or connected to a 3rd party software, i.e. Ruaumoko 2D [42] for the seismic analysis and EnergyPlus [43] for the energy simulation. In this study, the *pelicun* module developed by *Zsarnóczay* et al. [44], as an open source Python library, is shaped and connected to the existing workflow to quantify the post-earthquake repair costs.

The integrated risk analysis and probabilistic approach allow to assess the total economic (seismic + energy) loss, representing a valuable indicator to support stakeholders in investment decisions. The method also enable the calculation of the reliability of prediction associated with a building project, therefore, practitioners (engineers/designers) can achieve a better understanding of the overall building performance and risks associated with design alternatives. A range of possible economic savings can be computed rather than a single deterministic conservative or unconservative value and confidence levels can be identified to describe the expected building performance across multiple domains (seismic and energy); this would lead to more reliable estimations for clients investing their money. Furthermore, the method can be used to compare design solutions and identify the best solution among alternatives (Fig. 2). The probability of occurrence of a selected cost value and the probability of a specific cost interval (and related savings) can be computed and these parameters can be used to compare the design solutions. By assuming a target cost, the reliability (probability of success) and the unreliability (probability of failure) of achieving the target can be assessed, as well as the corresponding probability that the prediction will deviate from the target. Consequently, stakeholders could make more-informed decisions and develop strategies to decrease the risks of a building project, e.g. by adopting a resilient-enhanced solution leading to reduced losses or by applying a technology able to narrow down the cost distribution curve (lower dispersion value).

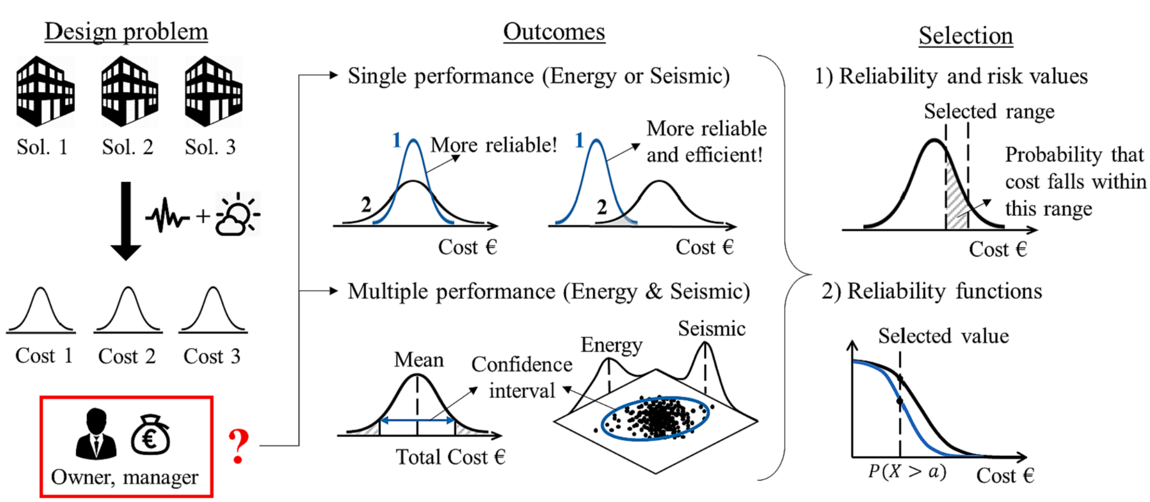

Fig. 2. Potential applications of the probabilistic-based methodology.

3. Application to a case study

The effectiveness of the integrated probabilistic-based approach to support investment decisions is assessed by considering a multi-storey Reinforced Concrete (RC) building as case study. The building scheme derives from a previous study developed by *Bianchi* et al. [37]. The five-storey building has a rectangular floor plan (32 m long × 18 m wide), a total height of 19 m and an inter-storey height of 3.8 m (Fig. 3). The ground, first and second floors are open-plan office floors, the third and fourth levels are residential, the building roof is not accessible.

The primary load-bearing structure consists of RC frames (external beams: 0.40 m × 0.75 m; internal beams: 0.30 m × 0.6 m; external columns: 0.75 m × 0.4 m; internal columns: 0.40 m × 0.40 m), RC walls (0.40 m × 6 m) and hollow-core slabs (0.25 m thick, one-way spanning). The seismic resisting system comprises two lateral frames in the longitudinal direction and two shear walls in the transverse direction. The structural/seismic design is developed by referring to the above-mentioned building scheme, geometry and related vertical loads (self-weight, live loads) and considering the seismic hazard of two Italian cities: 1) Messina, a high-seismicity zone; 2) Bolzano, a low-seismicity zone. The cities are characterized by different climatic conditions: 1) Messina has a warm temperate Mediterranean climate with dry, warm summers and moderate, wet winters (average annual temperature: 17.2 °C); 2) Bolzano has a semi-continental climate, with hot summers and cold winters, and significant precipitation even in the driest month (average annual temperature: 8.2 °C).

Two structural connections are designed and compared for both the beam-column joints and the wall/column-foundation system: 1) monolithic cast-in-situ concrete connections; 2) low-damage PRESSS connections [25,26] consisting of external dissipaters and internal post-tensioned tendons/bars (beams/walls). The seismic design of both systems is carried out at the Ultimate Limit State (ULS) level (475 years return period earthquake, Importance Level/Class 2 [45]). A Direct Displacement-Based Design (DDBD) procedure [46,47] is implemented by assuming specific inter-story drift limits as suggested by design code/guidelines and/or good practice and/or material strain limits (*Building Design* in Python *Seismic Module*). Table 1 provides a summary of the key parameters obtained from the seismic design. The internal actions (shear, bending moment, axial force) on the structural members, derived from the DDBD outcomes through an equilibrium approach, are then used to design the seismic beams, columns and walls, i.e. to compute the steel reinforcement (diameters, number of bars) for the monolithic connections and the post-tensioned tendons/bars (initial force, type) and the external dissipaters (fuse diameter and length) for the PRESSS hybrid connections (*Connection Design* in Python *Seismic Module*).

The building has two different facade systems: a) precast concrete panels in the frame (X) direction and b) glazed curtain walls in the wall (Y) direction. The concrete facades consist of 100 mm thick panels with a central opening embedding double glazed windows (0.3 Window-to-Wall Ratio). The heavy cladding panels are connected to the primary structure through bearing (bottom) connections designed to transfer the self-weight of the panel, while two (upper) connections are designed as lateral load resisting system: 1) tie-back (push–pull) connections - as conventional solution -; 2) dissipative U-Shaped Flexural Plate (UFP) connections [31] - as low-damage alternative - both designed considering the seismic force by code formulations [45], assuming a connection drift level at yielding of 0.2 % and accounting for stress and deformation checks. The glazed facades are stick-systems made of 8 + 16 + 8 mm thick double glazing units, linearly supported on the edges through silicone gaskets and connected (dry connections) to an aluminum frame consisting of continuous mullions supporting the transoms. The direct contact between glass panels and aluminum frame is avoided by means of internal clearance, equal to 6 mm for the annealed glass panels adopted in the conventional solution and to 11 mm for the fully tempered glass panels used in the low-damage system.

Table 1
Design parameters from DDBD procedure (monolithic vs low-damage structure).

	Parameter	Monolithic Structure		Low-damage Structure	
		Frame direction	Wall direction	Frame direction	Wall direction
Messina	Design drift, θ_d [%]	1.5	1.2	1.5	1.2
	Design displ., Δ_d[mm]	160.1	158.0	166.5	160.7
	Effective mass, m_{eff} [t]	2785.1	2652.9	2785.1	2652.9
	Effective height, H_{eff} [m]	13,142	13,494	13,142	13,494
	Equivalent damping, ξ_e [%]	17.7	18.2	16.2	15.6
	Effective period, T_{eff} [s]	2.6	2.6	2.6	2.5
	Effective stiffness, K_e [kN/m]	16315.2	15540.7	16375.9	17244.5
	Ductility, μ	3.4	3.2	3.5	3.2
	Base shear, V_b [kN]	2611.5	2454.5	2725.9	2771.3
Bolzano	Design drift, θ_d [%]	0.8	0.7	0.8	0.7
	Design displ., Δ_d[mm]	89.6	90.7	93.6	94.7
	Effective mass, m_{eff} [t]	2785.1	2652.9	2785.1	2652.9
	Effective height, H_{eff} [m]	13,142	13,494	13,142	13,494
	Equivalent damping, ξ_e [%]	13.2	11.7	11.9	11.6
	Effective period, T_{eff} [s]	2.1	2.1	2.1	2.1
	Effective stiffness, K_e [kN/m]	24932.3	23748.8	25025.2	23836.9
	Ductility, μ	1.9	1.9	2.0	1.9
	Base shear, V_b [kN]	2234.5	2154.0	2343.3	2257.1

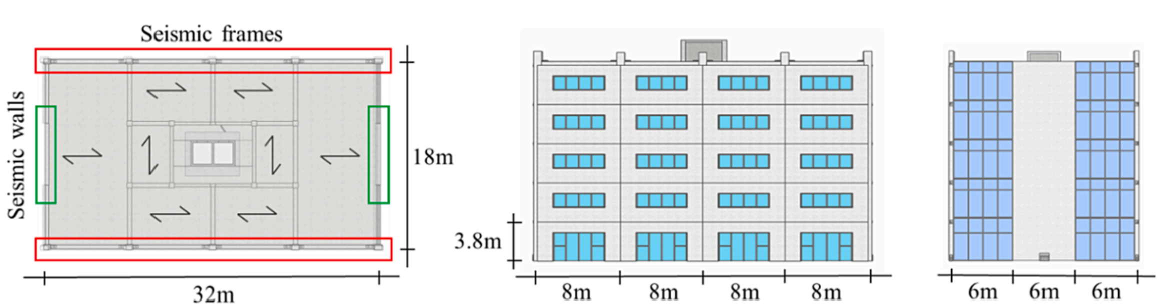

Fig. 3. Five-storey RC case-study building.

Furthermore, all the other architectural components (steel-frame drywall gypsum partitions, suspended ceilings), equipment (ideal HVAC systems) and contents (desktops, modular office tables, etc.) are identified to carry out the study. Design requirements are set for the internal comfort of building occupants. The cooling set point temperature is 24 °C and the heating set point temperature is 19 °C. For the internal heat gain of either office or residential floors, equipment load is 5 or 10 W/m^2, artificial lighting load is 10 or 5 W/m^2, while the density of occupation is 0.01 or 0.005 persons per square meter. The desired rate of outside air infiltration is 0.0003 m^3/s per square meter of floor. Different strategies are adopted to improve the building energy efficiency: 1) double glazing windows/units with low-e coatings; 2) prefabricated insulated concrete panels; 3) shading systems (solar blinds) for cooling load reduction; 4) reduction of air infiltration. All these strategies are combined with the seismic systems to define a total of 6 design solutions to be compared for both building locations (total cases: 6 × 2) (Fig. 4).

3.1. Probabilistic seismic analysis

The *Seismic Module* (*Modelling, Seismic Analysis, Loss assessment*) is employed to perform the seismic risk analysis. Input files (*.txt*) for Ruaumoko 2D software [42] are built in a Python environment and numerical investigations are performed to determine the overall building seismic performance through a lumped plasticity-based approach and non-linear static (pushover) analyses (as discussed in Section 2). The primary reinforced concrete structures are modelled considering rigid zones in the beam-column joints and concentrating the inelasticity at the end sections of the structural members, while fixed (translational/rotational) base joints are introduced neglecting the contribution of soil-structure interaction. The monolithic cast-in-situ structures, designed to achieve a beam sidesway collapse mechanism, are modelled by mono-dimensional elastic (Giberson) frame elements with plastic hinges at the connection interfaces. The flexural plastic hinges are defined by moment–curvature relationships and stiffness-degrading hysteresis rules (Takeda). The PRESSS post-tensioned rocking-dissipative structures are modelled as described in *Pampanin* et al. [48], that is, through elastic members with two rotational springs working in parallel at the end section(s): 1) one simulating the re-centering action of the post-tensioning cables/tendons (Multi-linear elastic); 2) the other one modelling the energy dissipation through the *Plug and Play* dissipaters (Ramberg-Osgood). Furthermore, the building facades are modelled through equivalent spring models calibrated by analytical formulations and/or experimental data [31,49]. The concrete facades are modelled by means of a linear elastic spring, representing the cladding panel with a central opening (window), shear springs (Ramberg Osgood) and rigid links simulating the top connection (tie-back or UFP) and bottom (bearing) connections, respectively [50]. As discussed in *Caterino et al.* [49], the glass facades are described by an equivalent spring model accounting for: 1) the aluminium frame and the rotational stiffness of its connections, 2) the glass panel-frame gap clearance and local impact associated with the gap closure, 3) the mechanical response of the gasket.

To include the epistemic uncertainties in the numerical modelling, material properties (strength, stiffness, deformations, mass density) for both concrete (structural members, concrete panels) and steel (rebars, rods, steel plates) and load/mass values are assumed as uncertain input parameters. Concerning the monolithic structure, coefficients of variation and probabilistic distributions (logNormal; Normal for concrete mass only) for the uncertain parameters are defined by referring to literature data [51–53] (Table 2). For the low-damage design solution, 1) concrete is assumed to vary following the same distribution, 2) uncertainty in dissipaters properties is the same assumed for the steel reinforcement (being the dissipaters obtained by necking down mild steel bars), 3) variation in the post-tensioned tendons/bars properties is

Table 2
Uncertainties in material properties - Monolithic Structure.

Parameter	Mean	COV	Distribution	Reference
Steel reinf. yield stress, f_{yk} [MPa]	450	0.05	logNormal	[52]
Steel reinf. Young mod., E_s [GPa]	210	0.05	logNormal	[51]
Steel reinf. ultimate strain., ε_{su} [%]	6	0.15	logNormal	[53]
Concrete compr. strength, f_{ck} [MPa]	50	0.20	logNormal	[52]
Concrete strain at peak stress, ε_{cc} [%]	0.21	0.10	logNormal	[53]
Concrete ultimate strain, ε_{cu} [%]	1	0.20	logNormal	[53]
Concrete density, ρ_c [kg/m^3]	2500	0.10	Normal	[52]

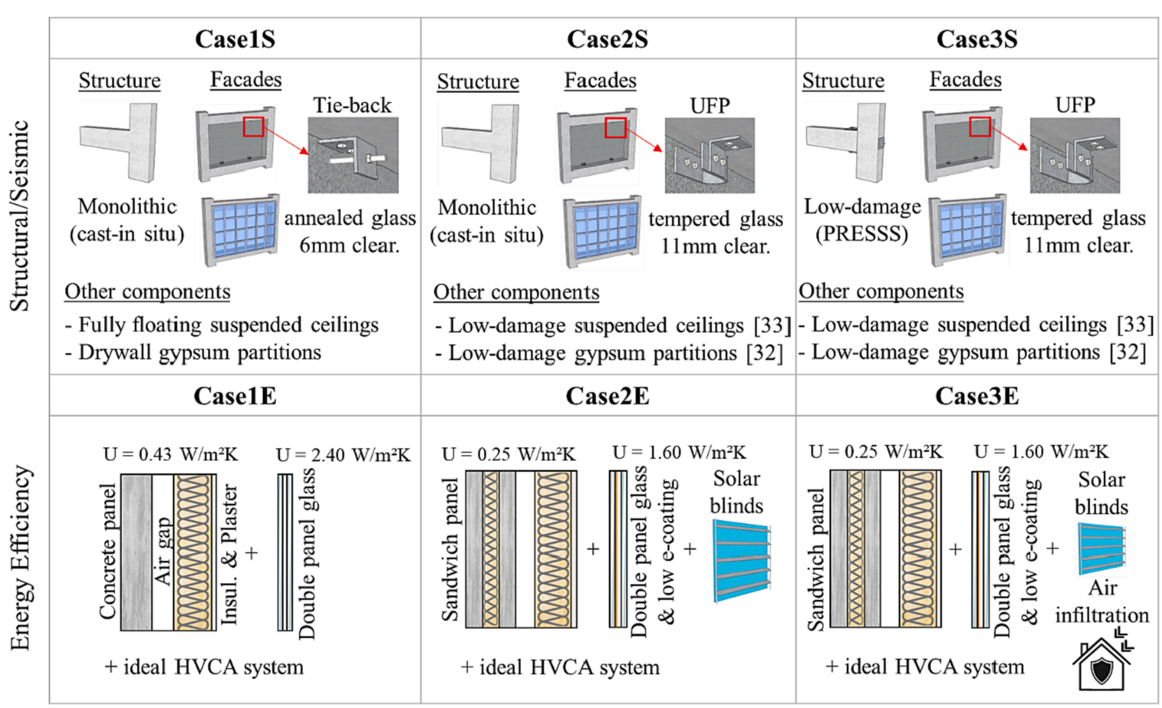

Fig. 4. Schematic drawing of the design solutions.

also included through a logNormal distribution for both yielding strength (f_{pty}) and elastic modulus (E_{pt}) with Coefficient Of Variation (COV) equal to 0.05 and mean values derived from existing catalogues (f_{pty} = 950/1670 MPa, E_{pt} = 205/195 GPa for the tendons/bars in the post-tensioned beams/walls). Latin hypercube sampling technique is applied to sample random variables from these probabilistic distributions, i.e. 300 samples to allow for higher accuracy in the predictive seismic response. The uncertain material properties are used to implement the *Building design* (DDBD method) and *Connection design* (targeting optimization of capacity vs demand) through the *Seismic Module* developed in Python. This allows to determine the variability in the moment-rotation curves for each structural connection, i.e. beam-column joints, column-foundation, wall-foundation, and identify the set of numerical models for the seismic risk analysis.

600 numerical models (300 for both frame and wall directions) are finally identified for each building configuration, leading to a total of 2,400 cases to be investigated (600 monolithic structures + 600 low-damage systems, in both high and low seismicity zones). Non-linear static (pushover) analyses of all these numerical models are performed to obtain the full range of building capacity curves for Cases1S, 2S and 3S. In order to apply the Capacity Spectrum Method [54], nine different levels of seismic intensity (from Immediate Operational to more than Collapse Prevention, as shown in Table 3) are considered. Combining the capacity (in terms of numerical pushover curves) and the demand (in terms of response spectra, built according to the Italian code [45] with C/D Ground type for Messina/Bolzano and T_1 Topographic Class for both cities) in the same Acceleration-Displacement Response Spectrum (ADRS) domain, the distribution of performance points is obtained for all the case studies (Fig. 5 for Case 1S: 600 models × 9 seismic intensities × 2 seismicity zones - Messina and Bolzano). The performance points allow to compute floor accelerations and storey drift ratios, representing key input data for the loss analysis.

The economic direct losses are estimated through the Python *pelicun* module [44] which follows the probabilistic-based methodology described in FEMA P-58 guidelines [55]. The loss assessment study is implemented for each scenario (300 models for Case1/2/3S in both seismicity zones) by considering the structural analysis results, i.e. the distributions of floor acceleration and storey drift ratio (drift range - envelope from min. to max. value - in Fig. 5 for ULS intensity) at the low-to-high seismic intensity levels. To account for uncertainty in record-to-record variability, dispersion is assumed for these estimates (in the order of 0.40–0.45 and 0.25–0.30 for drift and acceleration values, respectively) according to Table 5 and 6 of FEMA P-58 guidelines [55].

To conduct the loss assessment, fragility curves for all the building components need to be defined for the alternative design solutions (Case1S, 2S, 3S in Fig. 4). In this study, the fragility and consequence curves are built based on existing data collections for both the monolithic connections and the non-structural components [55,56], while the fragility data for the low-damage connections are derived numerically as described in *Bianchi* et al. [37]. Moreover, the total building replacement costs are estimated referring to regional public works price lists, already accounting for the specific labor cost, and the replacement time is based on man-days. The replacement cost of the monolithic structure includes the quantities of concrete and steel rebars, the cost of formworks, safety, excavation, foundations and geotechnical surveys, while the cost of the PRESSS structure accounts for the cost of dissipaters, tendons and their post-tensioning, the corrugated tube and the crane rental. The total replacement cost and time of the PRESSS structure result to be around 10 % higher and 25 % lower than the replacement cost (around 1300 €/m^2) and time (790 days) of the monolithic structure, respectively.

By combining structural analysis results, fragility and hazard, loss assessment analyses are finally performed. The large number of data obtained is elaborated in order to derive the probabilistic distributions of Repair Costs (RC) at each seismic intensity level or Mean Annual Frequency (MAF) by using curve-fitting techniques and goodness-to-fit tests (Table 4 provides the RC mean values for the nine hazard levels and all the design solutions; Fig. 6a shows the distribution of repair costs for a design solution and a specific intensity level along the RC/MAF curve).

To consider a more relevant indicator when making investment decisions, Expected Annual Losses (EALs) are calculated from the RC/MAF curves and expressed as a percentage of the total replacement cost. More specifically, 300 RC/MAF curves (Table 4 summarizes the mean RC values at selected MAF) are obtained for each design solution located in both seismicity zones, consequently, 300 EAL_S values are derived from

Table 4
Repair Costs (mean values) of the design solutions at the different intensity levels.

		Repair Costs [x 1000 €]		
	MAF [%]	Case1S	Case2S	Case3S
Messina	3.33	344.86	278.94	277.47
	2.00	546.67	400.04	322.71
	1.39	702.09	511.05	379.78
	0.99	940.50	689.04	463.46
	0.71	1334.81	1023.78	601.36
	0.50	1881.64	1545.17	844.90
	0.21	3095.46	2870.80	2079.28
	0.10	5570.60	5039.04	3695.03
	0.04	5729.87	5729.87	4647.98
Bolzano	3.33	155.43	145.85	173.00
	2.00	272.26	233.28	232.89
	1.39	396.26	308.75	262.82
	0.99	500.71	369.30	287.55
	0.71	581.13	417.60	315.56
	0.50	720.68	514.57	363.79
	0.21	1401.59	1056.75	616.96
	0.10	2379.79	2060.99	1150.61
	0.04	3473.92	3149.84	2545.54

Table 3
Response spectra parameters for high (Messina) and low (Bolzano) seismicity zones.

		Intensity level								
	Return period, Tr [years]	30	50	72	101	140	201	475	975	2475
Messina	Peak acc. ground A, a_g [g]	0.061	0.081	0.099	0.118	0.139	0.166	0.247	0.336	0.482
	Corner period, T_B [s]	0.148	0.154	0.160	0.163	0.165	0.168	0.176	0.184	0.199
	Corner period, T_C [s]	0.445	0.462	0.481	0.489	0.495	0.504	0.529	0.553	0.598
	Corner period, T_D [s]	1.842	1.925	1.996	2.072	2.157	2.266	2.589	2.943	3.530
	Amplif. factor, F_0 [-]	2.364	2.318	2.305	2.319	2.343	2.361	2.411	2.446	2.491
Bolzano	Peak acc. ground A, a_g [g]	0.019	0.025	0.028	0.032	0.036	0.039	0.052	0.063	0.079
	Corner period, T_B [s]	0.165	0.180	0.189	0.201	0.215	0.226	0.245	0.258	0.272
	Corner period, T_C [s]	0.494	0.541	0.568	0.603	0.646	0.679	0.736	0.773	0.815
	Corner period, T_D [s]	1.677	1.698	1.714	1.728	1.742	1.758	1.807	1.851	1.916
	Amplif. factor, F_0 [-]	2.552	2.521	2.498	2.487	2.503	2.516	2.596	2.699	2.819

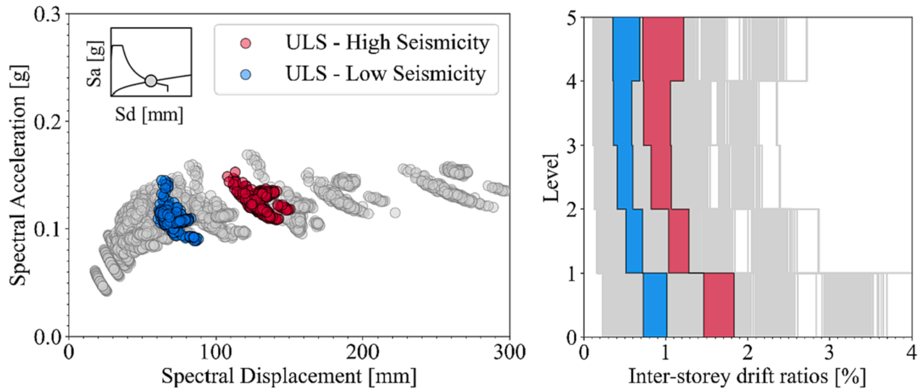

Fig. 5. Cloud of performance points and drift range for Case 1S (highlighting the expected drift values at ULS – 475 years return period - for both seismicity zones).

Table 5
Uncertainties in materials and design variations.

Parameter	Mean	COV	Distribution	Reference
Heating Set Point, HSP [C]	19	0.11	Normal	[59]
Cooling Set Point, CSP [C]	24	0.03	Normal	[60]
Equipment Density, E [W/m^2]	10	0.30	Normal	[38]
Lighting Density, L [W/m^2]	5	0.22	Normal	[38]
Concrete Conductivity, χ_c [W/mK]	1.491	0.20	Normal	[60]
Concrete Density, ρ_c [kg/m^3]	2179	0.07	Normal	[53]
Concrete Heat Capacity, C_c [J/KgK]	1000	0.11	Normal	[58]
Occupancy, O [ppl/m^2]	0.1	0.16	Normal	[58]
Glass Conductivity, χ_g [W/mK]	0.0192	0.53	Normal	[59]
Glass Density, ρ_g [kg/m^3]	2509	0.04	Normal	[59]
Glass Heat Capacity, C_g [J/KgK]	820	0.06	Normal	[59]

Table 6
Total losses (mean value, % of replacement cost) when different weights are assumed.

	Messina (High Seismicity)		Bolzano (Low Seismicity)	
	$w_S = 0.4$ $w_E = 0.6$	$w_S = 0.5$ $w_E = 0.5$	$w_S = 0.2$ $w_E = 0.8$	$w_S = 0.5$ $w_E = 0.5$
Case1S + E	0.68	0.67	0.82	0.63
Case2S + E	0.62	0.60	0.72	0.54
Case3S + E	0.53	0.51	0.55	0.41

the area underneath the loss curves (conceptual plot in Fig. 6a). It is worth noting that the advantage of applying low-damage technologies is already shown in Table 4, which highlights the reduction of repair costs when moving from Case1 (traditional), to Case2 (low-damage non-structural), to Case3 (integrated low-damage), especially for moderate-to-high earthquake intensities.

EALs values can be described in terms of probabilistic distributions accounting for modelling uncertainties (epistemic) and ground motion variability (aleatory) (Fig. 6b). The probabilistic EALs curves provide the risk associated with the building performance at different intensity levels and can be used to compare the design solutions. The significant benefit of low-damage technologies is demonstrated by the shift of the EAL curve to the left part of the graph, as well as by a lower dispersion which means more reliable/controllable outcomes. Considering the mean values, losses are reduced by 20/40 % for Case2S/3S (low-damage non-structural/ integrated) when compared to Case1S (traditional) for both low and high seismicity zones.

3.2. Probabilistic energy analysis

The *Energy Module* is employed to perform the probabilistic-based energy risk analysis. Input files (*.idf*) for EnergyPlus software [43] are built in Grasshopper environment (algorithmic modelling for Rhinoceros [57]) and manipulated in Python to account for modelling and hazard-related variability. Specifically, following the same approach used for the seismic assessment, uncertainties are considered for selected input parameters, that is, material properties (conductivity, density and heat capacity of both concrete and glass) for the outside

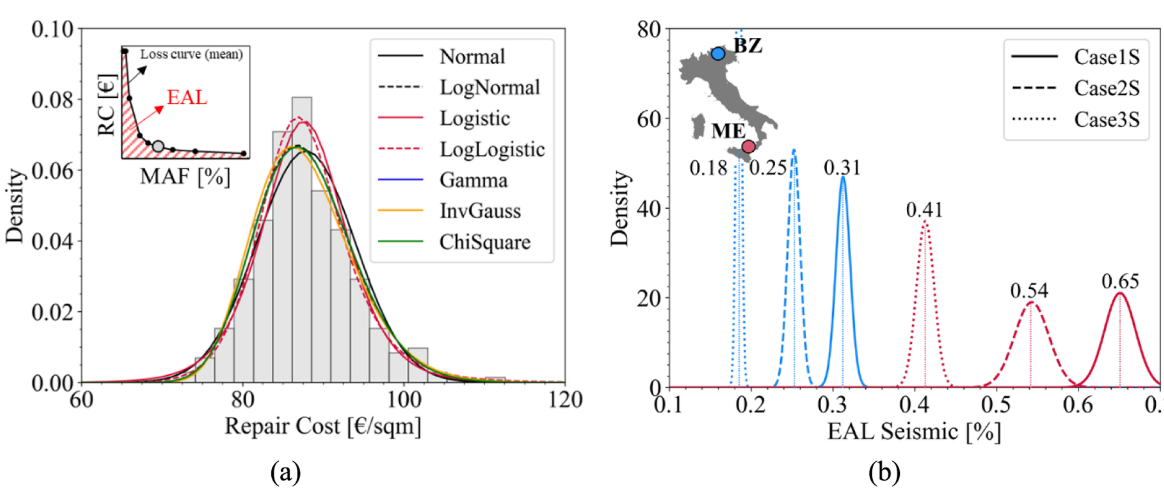

Fig. 6. Probabilistic seismic results: a) distribution of Repair Costs at moderate intensity level (Case1S, Bolzano); b) distributions of EAL_S for all the case-study buildings.

walls and design variations (equipment density, lighting density, load people, heating and cooling set points). Their (normal) probabilistic distributions and coefficient of variations are assumed based on available literature data [38,53,58–60] (Table 5). Moreover, the uncertainty in weather due to climate change is an important aspect when implementing energy risk assessment. To this end, the HadCM3 predictive model [61] is adopted to predict the weather variations in the building service life for both Messina and Bolzano. Referring to three different weather scenarios (years 2020, 2050 and 2080), the predicted yearly distributions of dry bulb temperature and domain of temperature variation (lower to upper boundary curve for each city) are presented in Fig. 7a, which shows the increase of temperature as a result of the climate change effect.

Latin hypercube sampling is implemented to retrieve values from the probabilistic distributions of the uncertain inputs and define a set of building cases to be investigated over the climate change-based meteorological year. Several hourly dynamic energy simulations are carried out to assess the building energy performance. In total, 1,800 simulations are performed, i.e. 300 (modelling + weather variation) × 3 (alternative design strategies) × 2 (locations). Results from the energy simulations are collected in terms of energy consumption (kWh/m^2) and elaborated to calculate the Energy Use Intensity (EUI), accounting for lighting, equipment, heating and cooling (Fig. 7b for all the case-study configurations and both cities, where the increase of Heating Degree Days, HDD, simulates the three climate-change meteorological years). Probabilistic distributions are obtained to describe the EUI variation (e.g. Fig. 8a for a specific case study), then energy costs are generated by converting the kWh/m^2 into € by using the electricity (0.22 € per kWh) and gas prices (0.09 € per kWh), including taxes and levies, provided by Eurostat for Italy. As highlighted by *Sun* et al. [38], these distribution values (EUI, costs) express the probability and risk in metrics more understandable for risk management. To use a common indicator for both seismic and energy analysis, the energy costs are finally converted into Expected Annual Losses (EAL_E) by dividing the cost of energy due to heating and cooling by the total building value, according to the definition provided by *Calvi* et al. [15] (Fig. 8b).

The numerical results (Fig. 8b) show that the energy economic losses are greater for the building located in Bolzano (low-seismicity), while the building in Messina is affected by higher dispersion; this is mainly due to the uncertainty in cooling setpoint combined with the climate-change weather variation. Moreover, energy efficiency strategies are more effective for the building in Bolzano due to the techniques adopted and mostly acting on thermal transmittance improvement. When compared to the EAL_S curves in the previous section, EAL_E distributions are affected by higher dispersion, which means a greater influence of uncertainties in the results.

3.3. Integrated seismic and energy analysis

EAL represents a valuable decision measure in building design. Typically, single values of EAL_S and EAL_E are assessed following a traditional - yet more advanced than common practice - approach. In this paper, it is proposed that the full range of possible combinations of EAL_S and EAL_E is identified for each building design, rather than a single (EAL_S, EAL_E) point in the EAL domain. This approach directly highlights the advantage of applying the proposed methodology when compared to a semi-deterministic procedure, meaning the derivation of EAL values not accounting for the proposed uncertainty quantification. The probabilistic approach allows to quantify the discrepancy between the expected losses and the predicted (probabilistic) estimations, thereby showing that the semi-deterministic method can lead to unconservative/unsafe results (Fig. 9a, for Case1S + E in Bolzano where Case1S + E = Case1S + Case1E, i.e. the building configurations are now identified by combining the seismic and energy strategies shown in Fig. 4).

Total cost estimations can be useful when making decisions about integrated performance, therefore probabilistic functions of losses are derived by considering cost combinations (EAL_{S+E}) for the design solutions and by elaborating these values through curve-fitting methods. However, following a multi-criteria decision-making approach, the EAL_{S+E} are herein computed by assigning relative weights to the seismic and energy losses rather than summing the single loss values:

$$EAL_{S+E} = w_S \bullet EAL_S + w_E \bullet EAL_E \tag{1}$$

The weighted sum from Eq. (1) allows the decision maker to make appropriate decisions based on the importance attributed to the single domain (seismic and energy); this choice is addressed by the specific case-study scenario (e.g. site, building use). For example, if the decision maker selects w_S = 20/40 % and w_E = 80/60 % for Bolzano (low-seismicity)/Messina (high-seismicity), the probabilistic curves (best fitting) in Fig. 9b are obtained. These functions provide the uncertainty associated with the total weighted EAL_{S+E} and can be used to compare the design solutions. Focusing on the mean values of these distributions, it is evident that an integrated seismic and energy assessment methodology provides a more comprehensive assessment of the building losses. Specifically, losses and savings can be highly underestimated if the single domains (energy or seismic) are considered independently (e.g. by 43 %

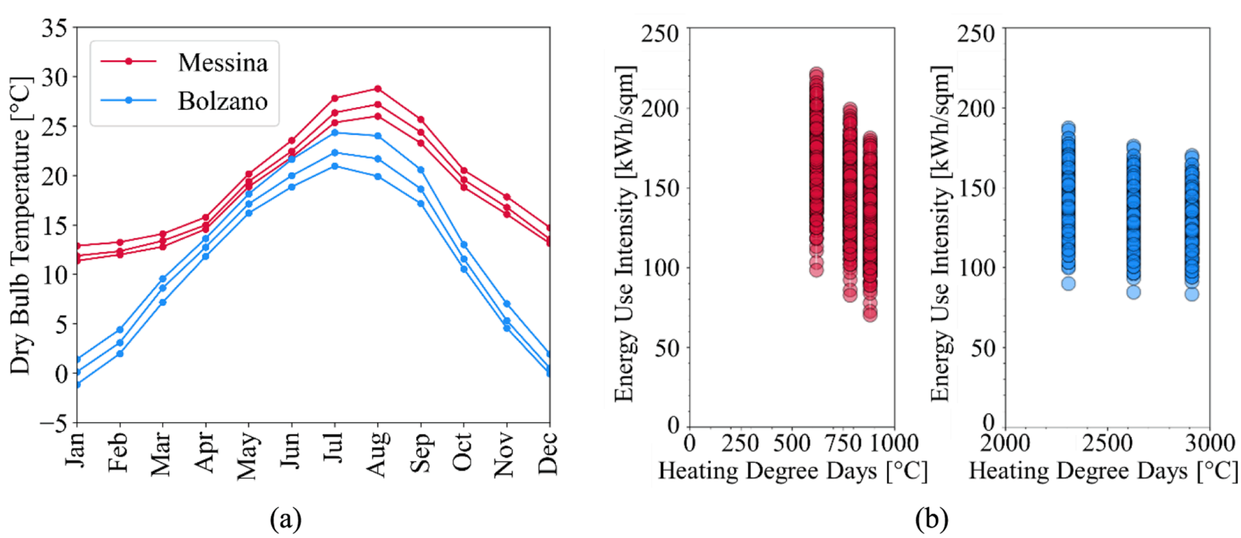

Fig. 7. a) Weather scenarios for both cities (years 2020, 2050, 2080, representing the lower, middle and upper curves) and b) cloud of points obtained from the energy simulations of all the case-study configurations (Case1E, 2E, 3E).

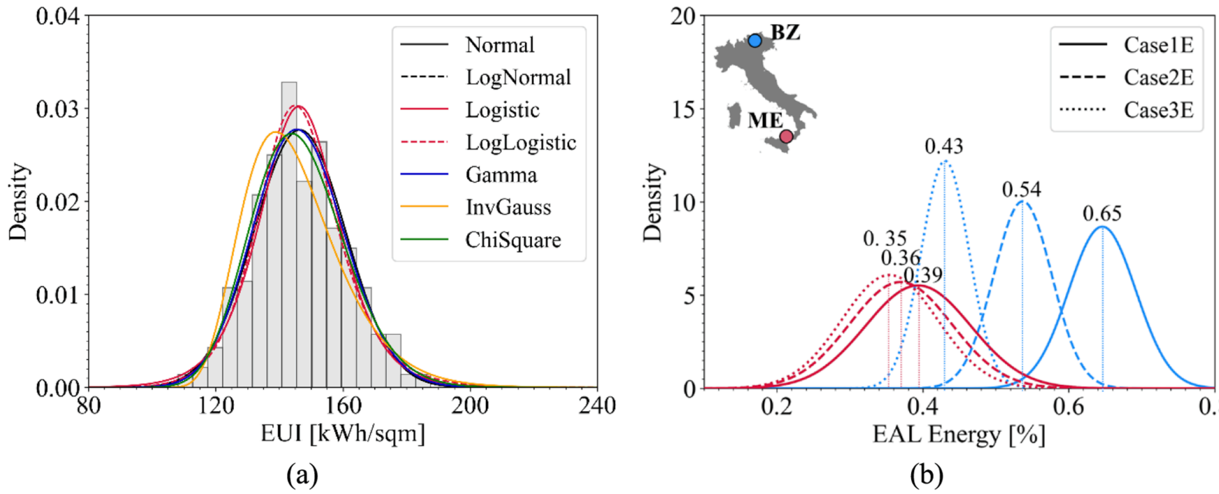

Fig. 8. Probabilistic energy results: a) distribution of EUI (Case 1E, Bolzano); b) distributions of EAL_E for all the case-study buildings.

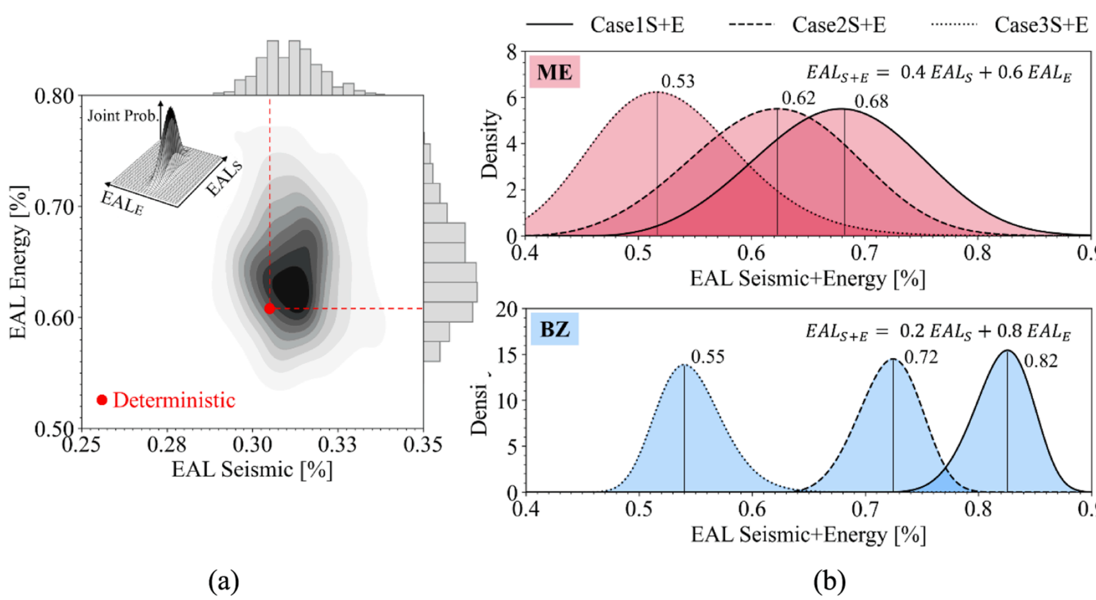

Fig. 9. a) Full range of energy and seismic EAL results for Case1S + E in Bolzano; b) Probabilistic distributions for the total seismic and energy cost.

for Messina Case1S + E vs Case1E, by 62 % for Bolzano Case1S + E vs Case1S). Moreover, for Messina (high seismicity), although higher savings (37 % - Case3S vs Case1S) are obtained in the seismic domain when compared to the energy domain (10 % - Case3E vs Case1E), savings achieve 22 % (Case3S + E vs Case1S + E) if the combined performance and integrated technologies are involved, even though EAL_S accounts for only 40 % of the final decision. This further confirms that greater savings can be obtained when seismic safety is involved in the selection process.

Furthermore, the influence of weighted factors on the total loss value is shown in Table 6. When the same weight (50 %) is assumed for seismic and energy costs, as considered in a typical - still advanced - approach, results might be highly affected by this assumption. When referring to Messina, losses are slightly modified and this is due to the high contribution of seismic losses in the overall cost. Conversely, the total loss significantly changes for Bolzano when a 50 % weight is assigned to both seismic and energy performance, leading to an underestimated/unsafe loss estimation when compared to the 20–80 % assumption. This confirms the importance of making decisions properly based on the specific scenario under investigation.

In addition to mean values of loss distributions, stakeholders might be interested in specific EAL values/intervals to decide what design solution should be used in a building project. For instance, by selecting a target cost, probabilistic results can be elaborated further to obtain reliability curves and reliability/risk values, as shown in Fig. 10. As far as the integrated loss is concerned, the target cost can be identified by assuming a desired energy and seismic risk class for the building and adopting the same weighted factors used to determine the probabilistic distributions (w_S = 40 %, w_E = 60 % for Messina). In this paper the risk classes are identified by referring to existing frameworks for seismic and energy risk classifications, i.e. the DM 65 [62] or so-called “Sisma Bonus” guidelines for the seismic classes (from A + to G, where A + identifies higher seismic performance) and the DM 26 [63] for the energy classification (from A4-1 to G, where A4 identifies higher energy efficiency). For example, assuming that the decision maker selects EAL_S $\leq$ 0.5 % (A + for the seismic class) and $EAL_E \leq$ 0.75 % (A2 for the energy class), the target cost - upper limit value - is EAL_{S+E} = (0.4 • 0.5 + 0.6 • 0.75)% = 0.65 % (Fig. 10). By assuming this limit, the alternative design solutions can be compared in terms of probability of being or not within the selected cost range (less than 0.65 %). Specifically, Fig. 10b highlights that the high-performance system (Case3S + E), combining the integrated low-damage structure (Case3S) with the more efficient energy solution (Case3E), has a 96 % probability of being in that EAL

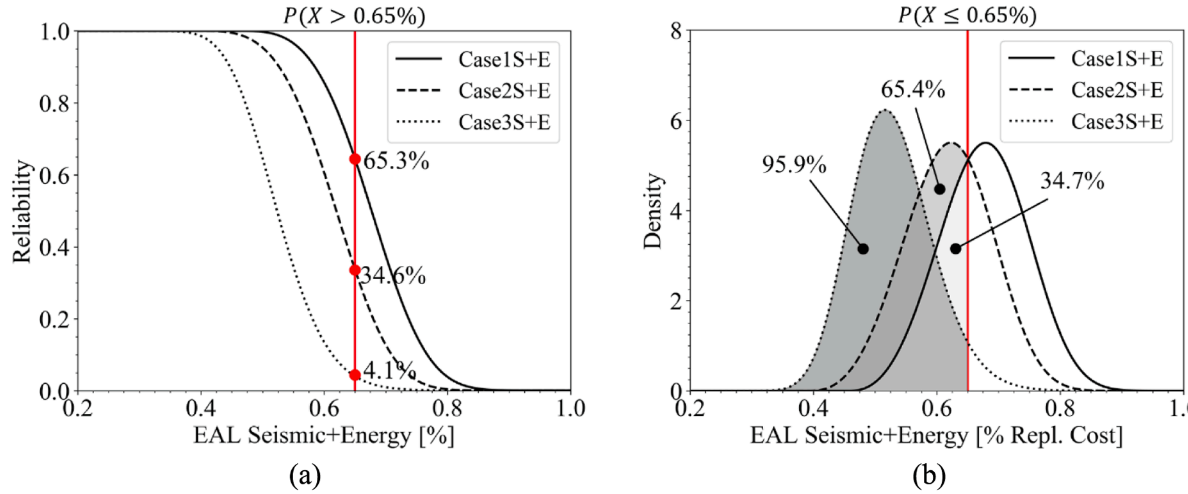

Fig. 10. For Messina (high-seismicity), assuming Class A + and A2 [60,61] for EAL_S and EAL_E: a) Reliability curves, b) Probabilistic distributions, and reliability/risk values.

range, while the benchmark system, combining the monolithic traditional structure (Case1S) with the basic energy efficient solution (Case1E), has only a 35 % probability. As part of the risk investment analysis, reliability curves and reliability/risk values could represent an effective means of assessing and comparing alternative design solutions.

4. Conclusions

The study explored the integration of seismic and energy performance of buildings in terms of economic losses, with the aim of informing design decisions. To improve the quality assurance in numerical predictions and obtain more reliable outcomes, a probabilistic risk analysis involving seismic and energy simulations was developed to account for modelling uncertainties and hazard (earthquake, weather) variability. The proposed procedure was implemented to compare alternative design configurations for a reinforced concrete case-study building, consisting of traditional vs low-damage technologies coupled with energy efficiency strategies. Probabilistic distributions of seismic, energy and combined economic losses were derived to gain knowledge of the reliability/risks associated with a specific design solution, as well as to support the building design by comparing design alternatives. The results demonstrated the potential of the proposed methodology in investment decision making by, for example, calculating the probability of cost/loss ranges. These outcomes might be used to make investment decisions, establish plans for possible losses or decrease the risks by applying advanced and more controllable technologies.

The research work has demonstrated the usability of the probabilistic-based approach in building design through a practical example of its application. The proposed procedure can be enhanced further, e.g. by accounting for site-specific weather uncertainties in addition to the climate change variability, by performing time-history analyses (although time-consuming) to assess the seismic performance, by implementing a more refined multi-criteria decision making approach, or by embedding the calculation of the environmental impacts within the proposed probabilistic-based approach. Further studies are also needed to develop a more comprehensive probabilistic design framework (e.g. including confidence levels) to support the selection of design solutions and, particularly, to demonstrate the application of the proposed approach and tool in real building projects.

CRediT authorship contribution statement

Simona Bianchi: Conceptualization, Investigation, Methodology, Project administration, Formal analysis, Data curation, Writing – original draft, Visualization, Funding acquisition. **Jonathan Ciurlanti:** Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization. **Mauro Overend:** Conceptualization, Supervision, Writing – review & editing. **Stefano Pampanin:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101029605 (H2020-MSCA-IF-2020 - SAFE-FACE - Seismic SAFety and Energy efficiency: Integrated technologies and multi-criteria performance-based design for building FACadEs) for Simona Bianchi. The authors also acknowledge the financial support of the Italian Ministry of Education, University and Research (MIUR) for funding the Doctoral Scholarships of Jonathan Ciurlanti.

References

[1] International Energy Agency. Global Status Report for Buildings and Construction 2021. Paris: UN Environment and International Energy Agency (IEA); 2021.
[2] Buildings Performance Institute Europe. Europe's building under the microscope. Brussels: Buildings Performance Institute Europe (BPIE); 2011.
[3] European Union. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency. Brussels: European Union (EU); 2012.
[4] Di Vece D, Pampanin S. Combined retrofit solutions for seismic resilience and energy efficiency of reinforced concrete residential buildings with infill walls. XVII ANIDIS Congress. Ascoli Piceno. Pisa University Press; 2019.
[5] Pampanin S. Reality-check and Renewed challenges in Earthquake Engineering: Implementing low-damage structural Systems – from theory to practice. Bull NZ Soc Earthq Eng 2012;45(4):137–60. https://doi.org/10.5459/bnzsee.45.4.137-160.
[6] Kam WY, Pampanin S, Elwood JK. Seismic performance of reinforced concrete buildings in the 22 February Christchurch (Lyttelton) earthquake. Bull NZ Soc Earthq Eng 2011;44(4):239–78. https://doi.org/10.5459/bnzsee.44.4.239-278.
[7] O'Reilly GJ, Perrone D, Fox M, Monteiro R, Filiatrault A. Seismic assessment and loss estimation of existing school buildings in Italy. Eng Struct 2018;168:142–62. https://doi.org/10.1016/j.engstruct.2018.04.056.

[8] Ramirez CM, Liel AB, Mitrani-Reiser J, Haselton CB, Spear AD, Steiner J, et al. Expected earthquake damage and repair costs in reinforced concrete frame buildings. Earthq Eng Struct Dyn 2012;41(11):1455–75. https://doi.org/10.1002/eqe.2216.
[9] Gkatzogias K, Tsionis G, Romano E, Negro P, Pohoryles D, Bournas D, Sousa L. Integrated techniques for the seismic strengthening and energy efficiency of existing buildings. JRC Conference and workshop report; 2021.
[10] Marini A, Passoni C, Belleri A, Feroldi F, Preti M, Metelli G, et al. Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept. Eur J Environ Civ Eng 2022;26(7):2475–95. https://doi.org/10.1080/19648189.2017.1363665.
[11] Artino A, Evola G, Margani G, Marino EM. Seismic and Energy Retrofit of Apartment Buildings through Autoclaved Aerated Concrete (AAC) Blocks Infill Walls. Sustainability 2019;11:3939. https://doi.org/10.3390/su11143939.
[12] Valluzzi MR, Saler E, Vignato A, Salvalaggio M, Croatto G, Dorigatti G, et al. Nested Buildings: An Innovative Strategy for the Integrated Seismic and Energy Retrofit of Existing Masonry Buildings with CLT Panels. Sustainability 2021;13(3):1188. https://doi.org/10.3390/su13031188.
[13] Passoni C, Guo J, Christopoulos C, Marini A, Riva P. Design of dissipative and elastic high-strength exoskeleton solutions for sustainable seismic upgrades of existing RC buildings. Eng Struct 2020;221:111057. https://doi.org/10.1016/j.engstruct.2020.111057.
[14] Zanni J, Cademartori S, Marini A, Belleri A, Passoni C, Giuriani E, et al. Integrated Deep Renovation of Existing Buildings with Prefabricated Shell Exoskeleton. Sustainability 2021;13(20):11287. https://doi.org/10.3390/su132011287.
[15] Calvi GM, Sousa L, Ruggeri C. In: Multi-hazard Approaches to Civil Infrastructure Engineering. Cham: Springer International Publishing; 2016. p. 165–208. https://doi.org/10.1007/978-3-319-29713-2_9.
[16] Passoni C, Marini A, Belleri A, Menna C. Redefining the concept of sustainable renovation of buildings: State of the art and an LCT-based design framework. Sustainable Cities and Society 2021;64:102519. https://doi.org/10.1016/j.scs.2020.102519.
[17] Menna C, Del Vecchio C, Di Ludovico M, Mauro GM, Ascione F, Prota A. Conceptual design of integrated seismic and energy retrofit interventions. J Build Eng 2021;38:102190. https://doi.org/10.1016/j.jobe.2021.102190.
[18] Caruso M, Pinho R, Bianchi F, Cavalieri F, Lemmo MT. Integrated economic and environmental building classification and optimal seismic vulnerability/energy efficiency retrofitting. Bull Earthq Eng 2021;19(9):3627–70. https://doi.org/10.1007/s10518-021-01101-4.
[19] Clemett N, Carofilis Gallo WW, O'Reilly GJ, Gabbianelli G, Monteiro R. Optimal seismic retrofitting of existing buildings considering environmental impact. Eng Struct 2022;250:113391. https://doi.org/10.1016/j.engstruct.2021.113391.
[20] Menna C, Felicioni L, Negro P, Lupíšek A, Romano E, Prota A, et al. Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings. Sustainable Cities and Society 2022;77:103556. https://doi.org/10.1016/j.scs.2021.103556.
[21] Jin Q, Overend M. A prototype whole-life value optimization tool for facade design. J Build Perform Simul 2013:217–32. https://doi.org/10.1080/19401493.2013.812145.
[22] Montali J, Sauchelli M, Jin Q, Overend M. Knowledge-Rich Optimisation of Prefabricated Façades to Support Conceptual Design. Autom Constr 2019;97:192–204. https://doi.org/10.1016/j.autcon.2018.11.002.
[23] Clarke JA, Hensen JLM. Integrated Building Performance Simulation: Progress, Prospects and Requirements. Build Environ 2015:1–13. https://doi.org/10.1016/j.buildenv.2015.04.002.
[24] Pampanin S. Towards the "Ultimate Earthquake-Proof" Building: Development of an Integrated Low-Damage System. Ansal A. Editors. Geotechnical, Geological and Earthquake Engineering. Springer. Nature 2015:321–58. https://doi.org/10.1007/978-3-319-16964-4_13.
[25] Priestley MJN. Overview of PRESSS Research Program. PCI J 1991;36(4):50–7.
[26] Priestley MJN, Sritharan S(, Conley JR, Stefano Pampanin S. Preliminary Results and Conclusions From the PRESSS Five-Story Precast Concrete Test Building. PCI J 1999;44(6):42–67.
[27] Palermo A, Pampanin S, Buchanan AH, Newcombe MP. Seismic design of multi-storey buildings using Laminated Veneer Lumber (LVL). NZ Soc Earth Eng Conference Wairakei, New Zealand 2005.
[28] Palermo A, Pampanin S, Buchanan A. Experimental investigations on LVL seismic resistant wall and frame subassemblies. In: 1st ECEES Conference. Geneva, Italy; 2006.
[29] Christopoulos C, Pampanin S, Priestley MJN. Performance-based seismic response of frame structures including residual deformations. Part I: single-degree-of-freedom systems. J Earthq Eng 2013;7(1):97–118. https://doi.org/10.1080/13632460309350443.
[30] Sause R, Ricles JM, Roke D, Seo CY, Lee KS. Design of self-centering steel concentrically-braced frames. 4th International Conference on Earthquake Eng. Taipei, Taiwan; 2006.
[31] Bair A, Palermo A, Pampanin S. Controlling Seismic Response using Passive Energy Dissipating Cladding Connections. In: NZSEE Conference. Wellington, New Zealand; 2013.
[32] Tasligedik AS, Pampanin S, Palermo A. Low damage seismic solutions for non-structural drywall partitions. Bull Earthq Eng 2014;13(4):1029–50. https://doi.org/10.1007/s10518-014-9654-5.
[33] Pourali A, Dhakal RP, MacRae GA, Tasligedik AS. Fully-floating suspended ceiling system: experimental evaluation of the effect of mass and elastic isolation. In: 16th World Conference on Earthquake Engineering. Santiago, Chile; 2017.
[34] Perrone D, Filiatrault A, Peloso S, Brunesi E, Beiter C, Piccinin R. Experimental seismic performance evaluation of suspended piping restraint installations. Bull Earthq Eng 2020;18:1499–524. https://doi.org/10.1007/s10518-019-00755-5.
[35] Johnston HC, Watson CP, Pampanin S, Palermo A. Shake table testing of an integrated low-damage frame building. In: NZSEE Conference. Auckland, New Zealand; 2014.
[36] Bianchi S, Ciurlanti J, Perrone D, Filiatrault A, Costa AC, Candeias PX, et al. Shake-table tests of innovative drift sensitive nonstructural elements in a low-damage structural system. Earthq Eng Struct Dyn 2021;50(9):2398–420. https://doi.org/10.1002/eqe.3452.
[37] Bianchi S, Ciurlanti J, Pampanin P. Comparison of traditional vs low-damage structural & non-structural building systems through a cost/performance-based evaluation. Earthq Spectra 2021;37(1):1–20. https://doi.org/10.1177/8755293020952445.
[38] Sun S, Kensek K, Noble D, Schiler M. A Method of Probabilistic Risk Assessment for Energy Performance and Cost Using Building Energy Simulation. Energy Build 2016;110(1):1–12. https://doi.org/10.1016/j.enbuild.2015.09.070.
[39] Bordbari MJ, Rastegar M, Seifi AR. Probabilistic Energy Efficiency Analysis in Buildings Using Statistical Methods. Iran J Sci Technol Trans Electr Eng 2020;44:1133–45.
[40] Helton JC, Davis FJ. Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. Reliab Eng Syst Saf 2003;81(1):23–69. https://doi.org/10.1016/S0951-8320(03)00058-9.
[41] Bianchi S, Ciurlanti J, Pampanin S. A SLaMA-based analytical procedure for the cost/performance-based evaluation of buildings. In: 7th COMPDYN Conference. Crete, Greece; 2019.
[42] Carr AJ. Ruaumoko Program for Inelastic Dynamic Analysis – User Manual. Christchurch: University of Canterbury; 2003.
[43] US Department of Energy's Building Technologies Office. EnergyPlus. DOE-BTO; 2001.
[44] Zsarnoczay A. NHERI-SimCenter/pelicun: pelicun v2.6. Zenodo; 2019.
[45] Ministero delle Infrastrutture. Aggiornamento delle Norme Tecniche per le Costruzioni, Supplemento ordinario n°8 alle G.U. n° 42 del 20/02/2018. Rome, Italy; 2018.
[46] Priestley NMJ, Calvi GM, Kowalsky MJ. Direct Displacement-Based Seismic Design of Structures. Pavia: IUSS Press; 2007.
[47] Pampanin S, Marriott D, Palermo A, New Zealand Concrete Society. PRESSS Design Handbook. Auckland: New Zealand Concrete Society; 2010.
[48] Pampanin S, Priestley NMJ, Sritharan S. Analytical modeling of the seismic behavior of precast concrete frames designed with ductile connections. J Earthq Eng 2001;5(3):329–67. https://doi.org/10.1080/13632460109350397.
[49] Caterino N, Del Zoppo M, Maddaloni G, Bonati B, Cavanna G. Occhiuzzi A Seismic assessment and finite element modelling of glazed curtain walls. Struct Eng Mech 2017;61(1):77–90. https://doi.org/10.12989/SEM.2017.61.1.077.
[50] Bianchi S, Ciurlanti J, Pampanin S Seismic vulnerability of non-structural components: from traditional solutions to innovative low-damage systems. SECED 2019 Conference. London, England; 2019.
[51] Hess PE, Bruchman D, Assakkaf IA, Ayyub BM. Uncertainties in Material and Geometric Strength and Load Variables. Naval Eng J 2002;114(2):139–66. https://doi.org/10.1111/j.1559-3584.2002.tb00128.x.
[52] Celarec D, Dolsek M. The impact of modelling uncertainties on the seismic performance assessment of reinforced concrete frame buildings. Eng Struct 2013;52:340–54. https://doi.org/10.1016/j.engstruct.2013.02.036.
[53] Barbato M, Gu Q, Conte JP. Probabilistic push-over analysis of structural and soil-structure systems. J Struct Eng 2010;136(11). https://doi.org/10.1061/(ASCE)ST.1943-541X.0000231.
[54] Freeman SA. Review of the development of the capacity spectrum method. ISET J Earthq Technol 2004;41(1):1–13.
[55] Federal Emergency Management Agency. Seismic Performance Assessment of Buildings, Volume 1 – Methodology. Washington DC, USA; 2018.
[56] Bianchi S, Pampanin S. Fragility Functions for Architectural Nonstructural Components. J Struct Eng 2022;148(10). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003352.
[57] McNeel R, et al. Rhinoceros 3D, Version 6.0. Robert McNeel & Associates: Seattle. WA 2010.
[58] Hopfe CJ, Hensen JLM. Uncertainty analysis in building performance simulation for design support. Energy Build 2011;43(10):2798–805. https://doi.org/10.1016/j.enbuild.2011.06.034.
[59] Corrado V, Mechri HE. Uncertainty and Sensitivity Analysis for Building Energy Rating. J Build Physics 2009;33(2):125–56. https://doi.org/10.1177/1744259109104884.
[60] Rodriguez GC, Andres AC, Munoz FD, Lopez JMC, Zhang Y. Uncertainties and sensitivity analysis in building energy simulation using macroparameters. Energy Build 2013;67:79–87. https://doi.org/10.1016/j.enbuild.2013.08.009.
[61] Chen Y. Environmental Adaptive Design: Building Performance Analysis for Climate Change. University of Southern California; 2015. Master dissertation.
[62] Ministero delle Infrastrutture. Linee guida per la classificazione del rischio sismico delle costruzioni, Allegato A. Decreto Ministeriale 65 of 07/03/2017. 2017.
[63] Ministero dello Sviluppo Economico. Linee guida nazionali per la certificazione energetica degli edifici, Allegato 1. Decreto interministeriale 26 Giugno 2015, Rome, Italy; 2015.