Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 2070-2084

ECCOMAS Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

ON THE INFLUENCE OF CLIMATE AND SEISMIC HAZARD CONDITIONS IN THE IDENTIFICATION OF OPTIMAL RETROFITTING STRATEGIES FOR RC BUILDINGS

R. Couto[1], **G. Mucedero**[1], **R. Bento**[2] **and R. Monteiro**[1,3]

[1] University School for Advanced Studies IUSS Pavia, Pavia, Italy
{rita.couto; gianrocco.mucedero; ricardo.monteiro}@iusspavia.it

[2] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
rita.bento@tecnico.ulisboa.pt

[3] CONSTRUCT, Faculty of Engineering, University of Porto, Portugal
rncm@fe.up.pt

Abstract

Past earthquakes have highlighted the vulnerability of existing reinforced concrete (RC) buildings, which constitute a large portion of the European building stock, most of which were not designed according to modern seismic codes. Moreover, their energy performance can also be highly unsatisfactory, leading to significant levels of energy consumption and CO_2 emissions. The assembling of a retrofitting approach with low environmental impact, capable of integrating increased structural performance with energy efficiency, is thus evermore essential. In this respect, recent studies were carried out with a particular emphasis on incorporating both interventions by identifying the optimal intervention among several feasible alternatives. This study investigates the influence of different climate and hazard conditions on the optimal retrofitting strategy, using a multi-criteria decision-making (MCDM) framework that includes a range of economic, social, and technical decision variables related to the building's seismic and energy performance. To this end, a case study application was carried out on a school building representative of such a building typology in Italy. Four seismic retrofitting solutions, each combined with three energy-based interventions, were assessed, considering two seismic hazard levels - medium and high - and three distinct climate conditions - cold, mild and warm. Finally, for each combination of seismic hazard and climate condition, an MCDM framework was employed to identify the optimal combination of seismic and energy-efficiency retrofitting schemes and the overall ranking of the different alternatives, aiming to investigate the influence of seismic hazard level and climate conditions on the optimal choice of a retrofitting intervention.

Keywords: Seismic Performance, Energy Performance, MCDM framework.

doi: 10.7712/120123.10543.20474

1 INTRODUCTION

The occurrence of past earthquakes highlighted the vulnerability of masonry-infilled reinforced concrete (RC) buildings, which represent a large part of the overall building stock in Mediterranean countries. Most of these buildings were built before the introduction of modern codes; hence they lack appropriate seismic resistance. Moreover, the energy performance of this building typology is highly unsatisfactory, resulting in high energy consumption, significant costs, and increased CO_2 emissions [1]. Recently, significant focus has been given to the development and evaluation of combined seismic and energy retrofitting schemes, with a view to minimise economic losses and environmental impacts and promote building renovation [2–4]. Given the wide range of possible structural and energy retrofitting schemes to couple in an integrated scheme, it is essential to proceed with methodologies that are capable of identifying optimal integrated retrofit solutions. Some of those methods, e.g., seismic resilience-based assessments, index-based methods, cost-benefit analyses and multi-criteria decision-making (MCDM) approaches, scrutinised and compared by Carofilis *et al.* [5], often consider a range of economic, social and technical decision variables (DVs) that are typical of interest to decision-makers. Different weights are usually given to the DVs, following the intuition of the decision-maker or determined through more rigorous criteria. Technical DVs related to the structural response and energy performance of existing buildings are of paramount importance due to their influence on the identification of the optimal retrofit alternative and are usually characterised by a higher weight when compared to other DVs.

A previous study by Clemett et al. [4] on seismic and energy retrofitting integration was conducted for a case-study building located in three different locations in Italy, characterised by cold (C), moderate (M) and warm (W) climates and similar medium-to-high levels of seismic hazard. The study presented here builds upon such a work [4], applying the same MCDM approach to the same case-study school building to understand the influence of different seismic and climatic demands on the choice of the optimal integrated retrofitting solution. The building was thus assumed to be located in three sites in Italy of similar medium-to-high (H) seismic hazard levels, with different climatic conditions, respectively characterised by cold (C), moderate (M) and warm (W) climates. Additionally, the building was also assumed to be located in three other sites in Italy of similar medium (M) seismic hazard levels and, again, with different cold (C), moderate (M) and warm (W) climate conditions.

2 MULTI CRITERIA DECISION MAKING METHODOLOGY

One of the most appealing frameworks for the identification of optimal combined seismic and energy efficiency retrofitting interventions is based on an MCDM approach, which considers the performance of different retrofit alternatives across a broad range of decision variables (DVs) and uses a weighted average method to identify the optimal solution. This methodology, employed in the present study, has been described extensively by Caterino *et al.* [6] and Carofilis *et al*. [5].

The process initiates with the identification of a set of DVs, with which the performance of each retrofitting alternative will be assessed, and to each of which weight is assigned as a function of its importance. The Analytical Hierarchy Procedure (AHP) [7] or decision-maker expertise can be used to define the weight values. Once the values for each DV are obtained, a decision matrix (DM) can be assembled, containing the associated values for each retrofit intervention. The values of the DM are then normalised, and the ideal and least ideal solutions for each DV are determined, allowing a comparison with each of the proposed design alternatives. To do so, the n-space Euclidean distance between the DM values for the design alternative and the ideal and least ideal alternatives is used. Finally, the relative closeness of each alternative to the least ideal solution is calculated, and the alternative with the highest relative closeness (i.e., the furthest alternative from the least ideal) is chosen as the preferred one.

The DVs and corresponding weights applied in this study, presented in Table 1, are the ones proposed by Clemett *et al*. [4]. The weight vector was defined employing the AHP and the professional judgment of the authors. DVs like C1, C2, and C3 are considered more relevant to the choice of the optimal retrofit solution, demonstrated by their greater weight, while DVs like C6 and C7 are considered less relevant. The choice of the weight vector was found to be the most significant source of uncertainty in the MCDM procedure and, consequently, in its results, as reported by Carofilis *et al*. [8]. Interested readers are referred to Clemett *et al*. [4] for more details on the MCDM framework used herein, as well as on the definition of both decision matrix and weight vectors.

Group	Decision Variables		Weight
Economic	C1	Installation cost	0.15
	C2	Expected annual costs	0.19
Environmental	C3	Expected life-cycle environmental impacts (LCEI)	0.18
Social	C4	Annual probability of failure	0.14
	C5	Duration of works	0.13
	C6	Architectural impact	0.06
Technical	C7	Need for specialized labour/design knowledge	0.05
	C8	Required intervention at the foundations	0.10

Table 1: Decision variables and corresponding weight

3 CASE-STUDY

The case-study school building is a RC building with URM infills located in Isola del Gran Sasso d'Italia (Italy) and built between the 1960s and 1970s [9]. The school has two storeys, with a floor area of approximately 630m^2 and interstorey heights of 3.75m and 4.25m for the first and second floors, respectively. The structural system consists of two-way RC moment resisting frames in the longitudinal and transverse directions, and unreinforced masonry infills (URM) are present along the building façade with large openings to accommodate windows and doors. A more detailed description of the building, along with its architectural plans and elevations, can be found in Prota *et al.* [9]. A numerical model of the case-study building was developed using OpenSees [10], as presented in Figure 1:

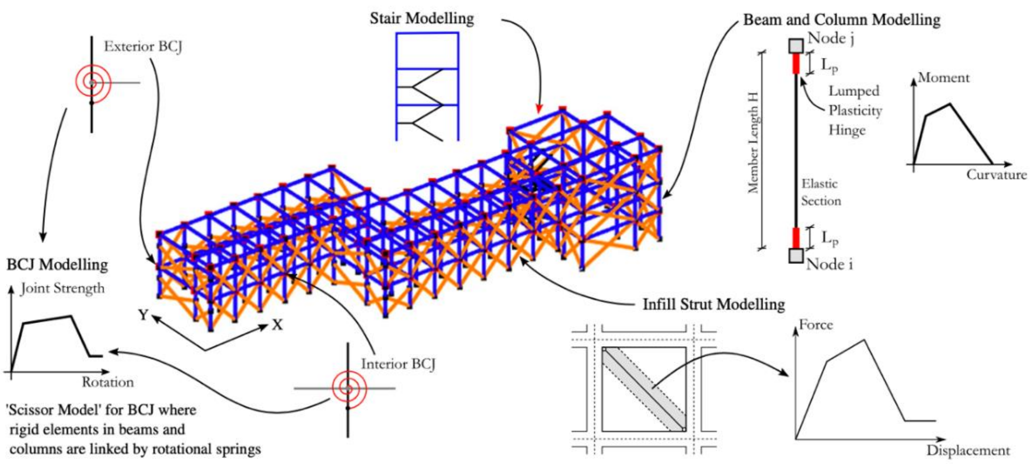
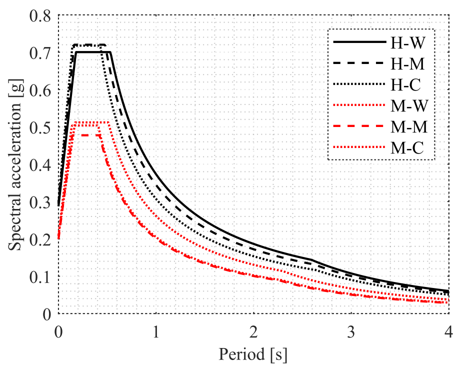
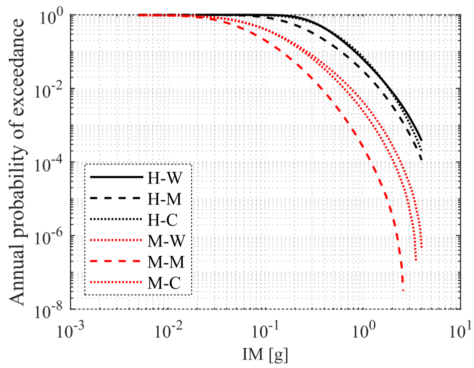


Figure 1: Three-dimensional representation of the numerical model developed in OpenSees [4]

The building was assumed to be located in six different sites in Italy: (i) a first set of three locations of similar high (H) seismic hazard level, but with different climatic conditions, namely Città di Castello, Isola del Gran Sasso d'Italia and Catania, respectively characterised by cold (H-C), moderate (H-M) and warm (H-W) climates; and (ii) a second set of three additional locations of low seismic hazard level. Additionally, the building was also assumed to be located in three other sites in Italy of similar medium (M) seismic hazard level, but, again, with different climatic conditions, namely Vicenza, Serravalle Pistoiese and Cirò Marina, respectively characterised by cold (M-C), moderate (M-M) and warm (M-W) climates. The acceleration response spectrum and the hazard curve for each assumed location are displayed in Figure 2, while the specific features of each site are summarized in Table 2. Each location is labelled by the corresponding level of hazard (medium or high) and climatic condition (cold, moderate and warm).



(a)



(b)

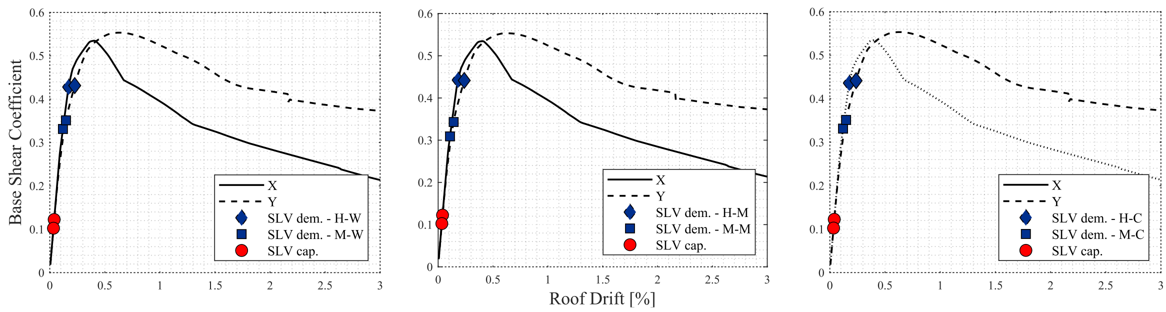
Figure 2: (a) Acceleration response spectrum and (b) hazard curve for the six locations analysed.

City	ID	Coordinates	Level of seismicity	PGA (SLV) [g]	Climatic zone	Heating Degree Days (HDD)
Città di Castello	H-C	43.4700°N, 12.2314° E	High (H)	0.30	Cold (C)	2347
Isola del Gran Sasso d'Italia	H-M	42.5056°N, 13.6592° E	High (H)	0.29	Moderate (M)	2038
Catania	H-W	37.5013°N, 15.0742° E	High (H)	0.29	Warm (W)	833
Vicenza	M-C	45.5455° N, 11.5354° E	Medium (M)	0.21	Cold (C)	2371
Serravalle Pistoiese	M-M	43.9059° N, 10.8330° E,	Medium (M)	0.20	Moderate (M)	2010
Cirò Marina	M-W	39.368° N, 17.128° E	Medium (M)	0.21	Warm (W)	845

Table 2: Summary of the seismic hazard and climate conditions at each of the selected sites.

3.1 Preliminary Seismic and Energy Assessment

Firstly, a preliminary seismic assessment was conducted by means of a simplified nonlinear static procedure using an inverted triangular load pattern. Then, the displacements at which the structural elements (i.e. beam-column joints (BCJs), columns and beams) reached their deformation or strength limits for the life safety limit state (SLV), according to the NTC [11] requirements were estimated and compared with the performance point displacements of the structure for the SLV limit state, estimated using the N2 method [12]. The main structural weaknesses at the SLV limit state were identified as the moment capacity of BCJs and the shear failure of short columns adjacent to the partial height URM infills. Figure 3a-c presents the capacity curves obtained for the as-built structure, together with the roof displacement corresponding to the achievement of the first failure of a structural element and the estimated performance point, for the six locations considered. From Figure 3a-c, a few differences are observed in terms of the performance points, which are related to the slight differences in the response spectrum of each of the selected locations. For the locations with higher seismic hazard level, the capacity/demand ratio at SLV is about 23% and 16% for the X and Y direction, respectively. For the locations with medium seismic hazard level, as expected, the ratio at SLV increases, oscillating between 33% and 37 % for the X direction and 23% for the Y direction.



(a) (b) (c)

Figure 3: Pushover curve and SLV limit state demand (SLV dem.) and capacity (SLV cap.) for the as-built structure and the six locations considered according to the climatic zone: (a) warm (W), (b) moderate (M) and (c) cold (C).

The energy performance of the case-study building was assessed using the EDILCLIMA software [13], in which most of the modelling parameters, such as monthly weather data or internal heat gain, were defined according to the Italian energy-efficiency design standards [14,15] based on the building's occupancy typology. Four different thermal zones representing the basement, ground floor, first floor, and stairwells were included in the model, all assumed to be heated, with heating set-point temperature of 20°C. Ventilation of the building was assumed to be provided naturally (i.e., no mechanical ventilation plant). The thermal properties of the envelope elements were determined by defining the stratigraphy of each component's constituent materials, and the ensuing total thermal transmittances (U-values) are summarised in Clemett *et al.* [4]. Thermal bridges were included to correct the two-dimensional heat flow that occurs at the intersections of different building elements (i.e., external wall elements, external and internal wall elements, external walls and RC columns, external walls and roof/interstorey floors/ground floor, and external walls and windows). The heating energy was assumed to be supplied by a traditional natural gas boiler system. Domestic hot water was assumed to be provided by the same heating system used for space heating.

3.2 Selected Seismic and Energy Retrofitting Measures

Given the structural and energy deficiencies identified in the preliminary seismic and energy assessment, different corresponding retrofit measures (SRMs and ERMs, respectively) were applied to the case-study building. Regarding the SRMs, illustrated in Figure 4, three interventions were considered: S1 – local strengthening with carbon CFRP, S2 – global strengthening with additional concentric steel braces and S3 – CFRP strengthening combined with additional concentric steel braces. Additionally, for all SRMs, a seismic gap between the

URM infills and the RC frame was introduced, reducing both the column-infill interaction and the shear forces acting on the columns. Regarding the improvement of the energy performance of the building, three different combinations of ERMs, E1 to E3, were considered to reduce heat losses to the external environment and increase the energy efficiency of systems operating within the building. The invasiveness level of each intervention increases from E1 to E3 to meet the performance requirements described in the Italian Ministerial Decree [16]. The modelling assumptions for each EMRs can be found in Clemett *et al.* [4].

Finally, the three seismic interventions were coupled with each energy intervention, leading to nine possible combined retrofit alternatives. Each coupled intervention is designated by S_iE_i, where S_i and E_i correspond, respectively, to the reference number of the considered seismic and energy retrofit schemes. A summary of the SRMs and ERMs is provided in Figure 5.

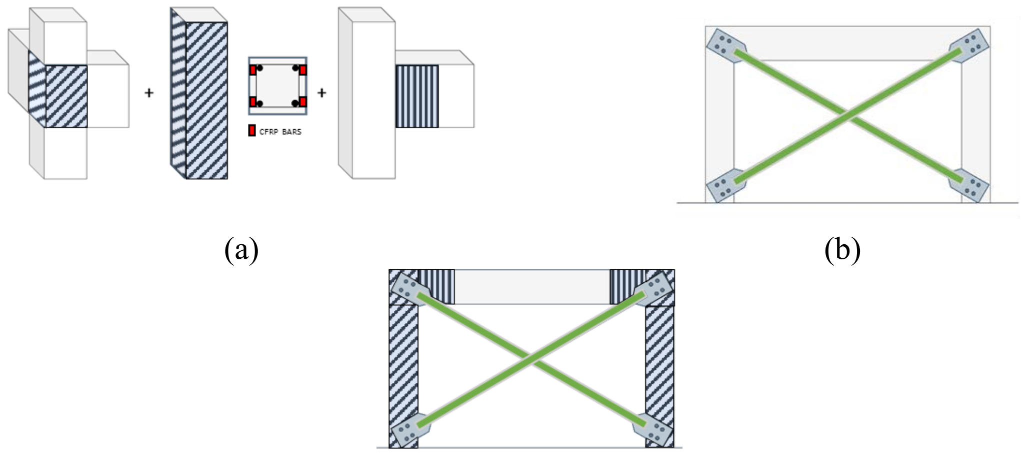


Figure 4: Scheme of the three structural retrofits: (a) S1 - local strengthening with carbon CFRP, (b) S2 - global strengthening with additional concentric steel braces and (c) S3 – CFRP strengthening combined with additional concentric steel braces.

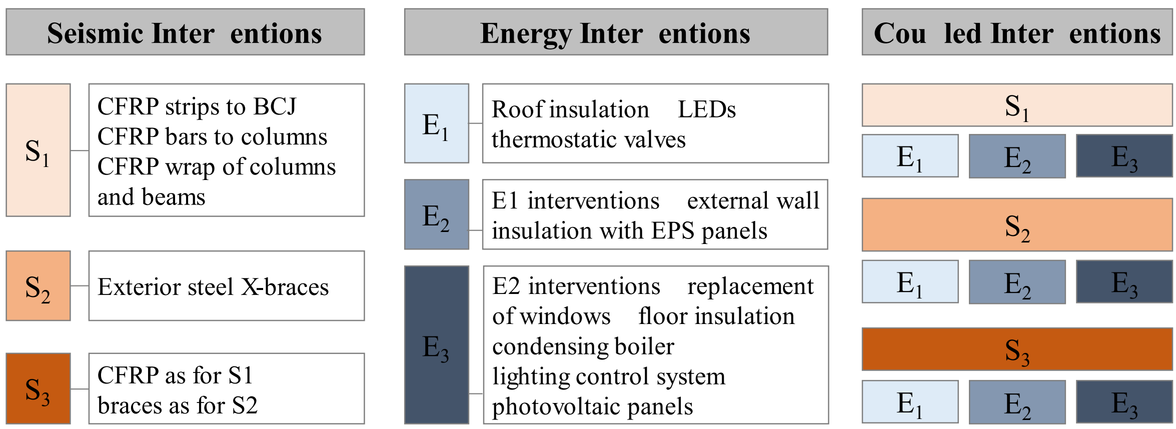


Figure 5: Seismic and energy retrofitting interventions

3.3 Post-Retrofit Seismic Performance Assessment

The capacity curves of the three seismically retrofitted alternatives and of the as-built structure as displayed in Figure 6(a)-(f). The displacements for which the retrofitted models attain the first structural element failure (due to exceeding deformation or strength capacity), as well as the performance point of the structure for the SLV limit state, are again indicated.

When compared with the as-built structure, all retrofitted models exhibit a decrease in the initial stiffness and lateral resistance due to the seismic gap introduced between the infills and the frame. Moreover, the greater difference between the X- and Y-directions is justified by the larger number of infills present in the longitudinal axis of the building.

All the retrofit interventions lead to an improvement in the structural performance of the building at the SLV limit state. S1 and S2 exhibit similar improvements, achieving capacities of 50% to 60% for the X direction and 40% to 80% for the Y direction of the code-specified demand. S3 exhibited the largest improvement, achieving a capacity of around 100% to 120% for the X direction and 170% to 190% for the Y direction.

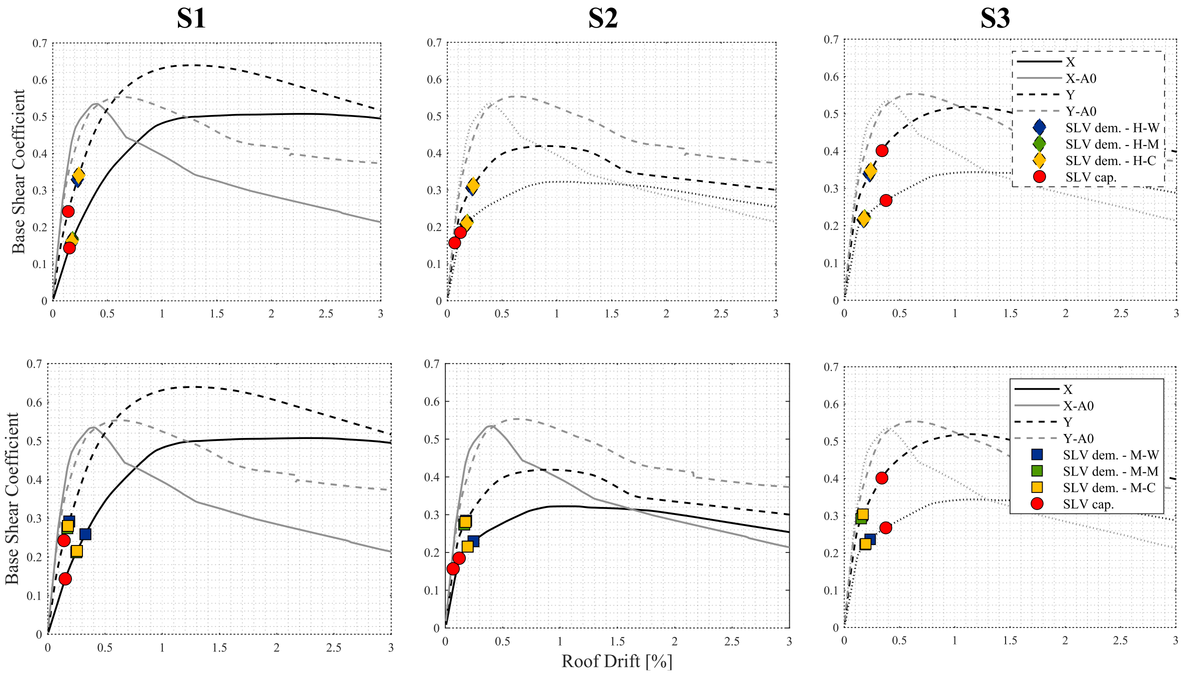


Figure 6: Pushover curves and SLV limit state demand and capacity for each retrofit alternative in function of the investigated site.

A comprehensive performance-based seismic assessment and loss analysis of the retrofitted case-study was then carried out, following the PEER-PBEE methodology [17], according to the following steps:

1. Characterisation of the seismic hazard at each of the selected sites and selection of suitable hazard-consistent ground motion sets for each site. The record sets were selected using an average spectral acceleration (AvgSa)-based procedure;
2. Quantification of the structural response through multiple-stripe analysis (MSA) for each site, using ground motion pairs selected in Step 1. The absolute peak floor acceleration (PFA), peak story drift (PSD) and peak floor velocity (PFV) were selected as engineering demand parameters (EDPs) to be used in the seismic loss assessment (Step 6);
3. Derivation of collapse fragility parameters through the MSA results. The median AvgSa and dispersion (β) values were modified to account for additional modelling uncertainty [18];
4. Development of the inventory of damageable components in the building, together with the definition of their potential damage states, expected repair cost and environmental

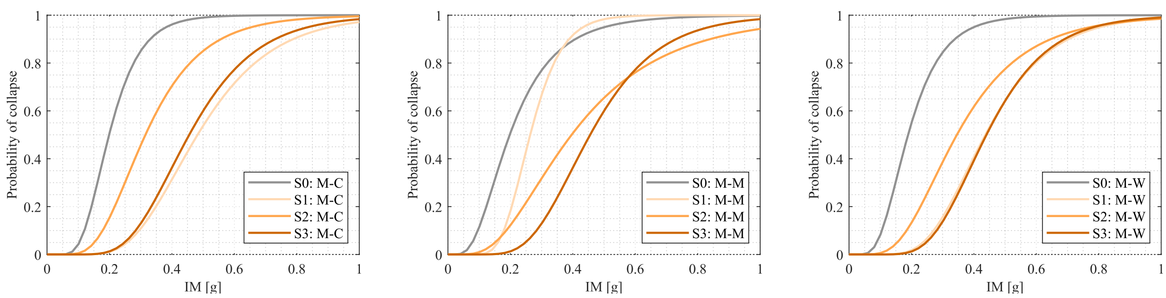
impact consequences. The presence of the ERMs was accounted for at this stage in terms of additional repair consequences to specific non-structural components due to their significant influence on the loss assessment [19–21]. The component inventory used herein was the one developed by Clemett *et al*. [22];

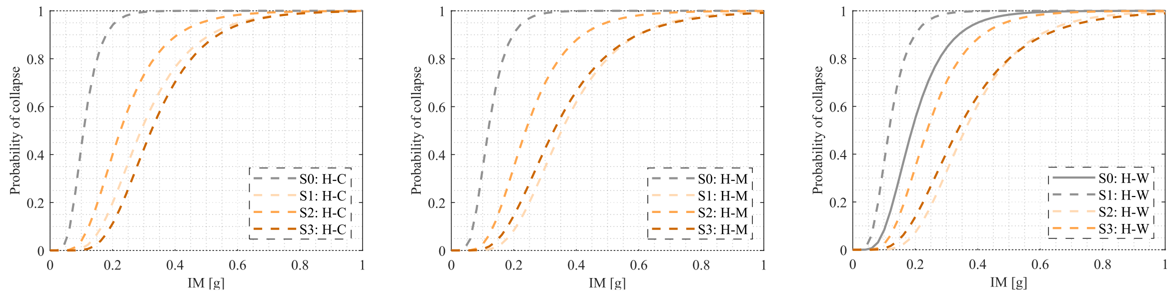
5. Estimation of the replacement cost and replacement environmental impacts for the as-built and retrofitted configuration of the case-study building. Table 3 summarises the replacement costs and EIs used in the loss assessment procedure for the as-built and retrofitted configurations. Both parameters increase with the severity of the intervention (from E_1 to E_3). For simplicity, it has been assumed that only the ERMs, as opposed to the SRMs, increase the building value;
6. Finally, the detailed seismic loss assessment is performed through PACT (FEMA P-58) [23] for each seismic and energy retrofit intervention combination. The outcomes of this assessment are the expected annual losses (EAL), the expected annual environmental impacts (EAEI) and the annual probability of failure (APF).

Alt.	Site Cold		Site Moderate		Site Warm	
	€	$kgCO_2e$	€	$kgCO_2e$	€	$kgCO_2e$
As-built	2,652,242	1,830,000	2,652,242	1,830,000	2,652,242	1,830,000
S_iE_1	2,703,835	1,869,777	2,700,684	1,867,485	2,688,077	1,858,315
S_iE_2	2,744,588	1,899,420	2,792,918	1,888,749	2,712,451	1,876,044
S_iE_3	2,890,738	2,005,724	2,858,340	1,982,159	2,841,825	1,970,146

Table 3: Replacement costs and EIs used in the loss analysis for each retrofit alternative and site considered.

The collapse fragility curves for the as-built and the four seismic retrofitting schemes are provided in Figure 7a-c, for the three climatic zones investigated (cold, moderate and warm, respectively) and hazard level. Dashed and solid lines are used for high and medium hazard level, respectively. Regardless of the climatic zone and hazard levels, all retrofit interventions improve the performance of the structure. Moreover, intervention S3 and S1 exhibit a similar performance for the cold (Figure 7a) and warm climate (Figure 7c) and for both hazard levels, while intervention S2, of global nature, presents the worst retrofitted structural performance, since it is not able to overcome the high demand/capacity ratio of poorly-detailed structural members. In case of moderate climate (Figure 7b), a shift on the structural performance of interventions S1 and S2 is observed for the medium hazard location (M-M), with the latter showing a greater improvement.

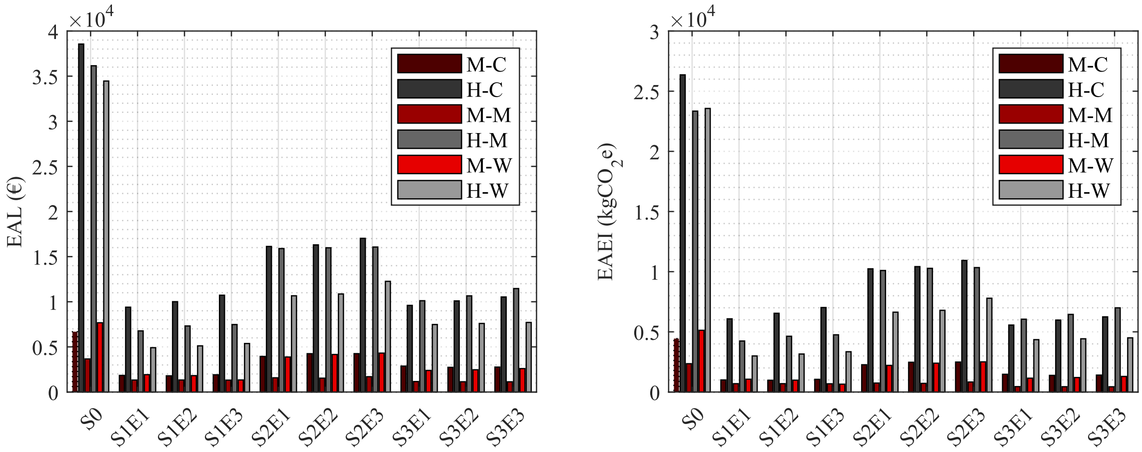




(a) (b) (c)

Figure 7: Collapse fragility curves of all retrofit interventions for the three sites considered: (a) warm (W), (b) moderate (M) and (c) cold (C), in function of the hazard level.

The main results of the seismic-related assessment (EAL and EAEI) for each coupled intervention and for each location are presented in Figure 8. The results obtained from the seismic loss assessment are in line with the observations based on the fragility curves: the intervention S2 shows higher EALs, EAEIs and APFs with respect to the other interventions. Interventions S1 and S3 present similar results, with the first showing a slightly better performance. In terms of location, the ones with higher seismic hazard, regardless of the climatic zone, consistently show greater values of EAL, EAEI and APF. Regarding the medium hazard site, a discrepancy on the results between Site M and the remaining is observed, which is justified by the hazard of this site which is slightly lower when compared with the remaining locations as observed in Figure 2.



(a) (b)

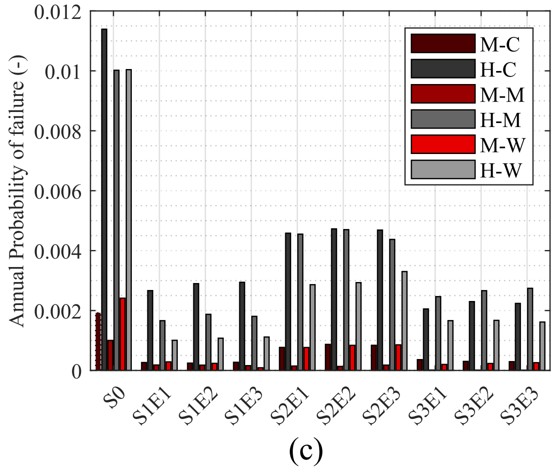


Figure 8: Seismic loss assessment results in terms of (a) EAL, (b) EAEI and (c) APF for each retrofit alternative and for each location analysed.

3.4 Post-Retrofit Energy Performance Assessment

The energy performance results of the as-built and retrofitted configurations at each site are summarised in Table 4**Error! Reference source not found.**. The parameters considered to evaluate the energy performance were the primary energy performance (PEC), the equivalent CO_2 emissions (Eq. CO_2), annual energy costs (AEC) and Italian energy class ratings. The influence of the climatic condition on the energy performance of the structure is evident, demonstrated by the difference in performance between the as-built structure located at the different sites, with the cold one being, as expected, the most demanding in terms of energy performance, exhibiting twice the quantities slightly, in terms of PEC, Eq. CO_2 and AEC were derived for the warm site. Moreover, all retrofit schemes enhanced the energy performance of the structure, which is in line with the severity of the intervention.

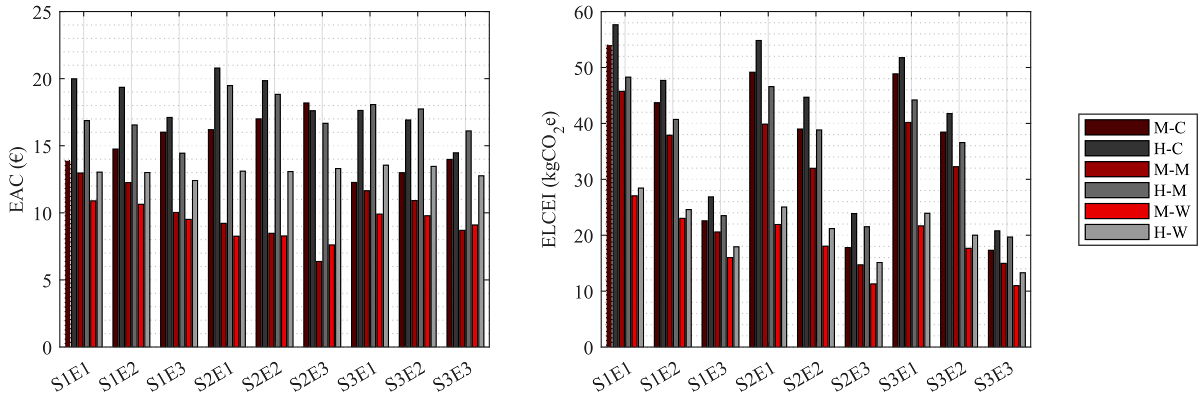
Site	Energy-retrofitting option	PEC (kWh/m^2)	Eq. CO_2 ($kgCO_2e$)	AEC (€)	Energy Class
Cold	As-built	372	92,192	14,878	F
	E_1	199.41	45,564	8,218	D
	E_2	73.22	16,919	3,445	C
	E_3	64.92	14,982	3,109	A2
Moderate	As-built	309	76,651	12,718	E
	E_1	221.76	52,476	8,765	D
	E_2	166.63	40,716	7,121	C
	E_3	64.92	14,982	3,109	A2
Warm	As-built	164	40,337	7,646	D
	E_1	106.4	26,118	5,102	C
	E_2	81.5	19,822	4,210	B
	E_3	40.34	8,828	2,198	A2

Table 4: Energy performance assessment summary for each energy-retrofitting intervention and for three different climatic conditions

4 MCDM RESULTS AND DISCUSSION

Once the results of the seismic and energy assessment for each coupled intervention were obtained, the decision matrices (DMs) were assembled. Table 5 summarises the DV values obtained for each coupled intervention per location investigated and Figure 9 summarises the results obtained for the decision variables C2 and C3 – total (seismic+energy) expected annual costs and life-cycle environmental impact. As expected, the results obtained for the decision variables C2 and C3 are lower for the three locations with moderate hazard level when compared to the locations with higher hazard level. Moreover, a trend between the different climatic sites is observed, independently from the hazard level: the obtained values for both DVs increase from the warm to the cold sites. This can be justified by the increased demand of energy from the warm to the cold conditions, which increases the annual energy costs and the environmental impact due to the installation of the ERMs. The same justification can be given to the decrease of these values from intervention E1 to E3, regardless of the hazard level.

Between different SRMs, different observations can be made between the two DVs. Regarding C2, and for the higher hazard level locations, intervention S2 has the highest values, followed by S1 and S3 which is justified by the seismic performance of each intervention. However, analysing the results obtained for the moderate hazard level locations, intervention S2 has the lowest values when compared to the other interventions. Even though the seismic losses for this intervention are higher (as was observed in Figure 8), the maintenance cost of this intervention is lower, when compared to the remaining interventions. Since the hazard level decreases, the importance of the maintenance cost is higher, resulting in a lower expected annual cost for this intervention. In the case of C3, intervention S1 presents the worst performance, followed by S2 and S3. This is justified by the higher environmental impact of intervention S1.



(a) (b)

Figure 9: Decision variables (a) C2 – expected annual cost and (b) C3 – expected life-cycle environmental impacts obtained for each retrofit alternative and for each location analysed.

Site	Alt.	C_1 (€)	C_2 (€)	C_3 ($kgCO_2e$)	C_4 ($x10^{-2}$)	C_5 (days)	C_6 (-)	C_7 (-)	C_8 (-)
M-C	S_1E_1	1209497	13.9	54.0	0.027	60	0.0227	0.0844	6.12
	S_1E_2	1293366	14.8	43.7	0.025	60	0.0227	0.0844	6.12
	S_1E_3	1521766	16.0	22.6	0.027	64	0.0227	0.0844	6.12
	S_2E_1	190167	16.2	49.2	0.077	22	0.0555	0.0135	16.49
	S_2E_2	274036	17.0	39.0	0.087	24	0.0555	0.0135	16.49
	S_2E_3	502435	18.2	17.8	0.084	29	0.0555	0.0135	16.49
	S_3E_1	250865	12.3	48.9	0.036	37	0.0934	0.0844	16.55
	S_3E_2	334734	13.0	38.4	0.030	37	0.0934	0.0844	16.55
	S_3E_3	563133	14.0	17.3	0.029	41	0.0934	0.0844	16.55
M-M	S_1E_1	1229555	13.0	45.7	0.018	61	0.0227	0.0844	5.71
	S_1E_2	1290386	12.3	37.9	0.019	61	0.0227	0.0844	5.71
	S_1E_3	1462370	10.0	20.6	0.016	65	0.0227	0.0844	5.71
	S_2E_1	183863	9.2	39.9	0.015	22	0.0555	0.0135	16.54

	S_2E_2	244694	8.5	32.0	0.014	24	0.0555	0.0135	16.54
	S_2E_3	416678	6.4	14.7	0.018	29	0.0555	0.0135	16.54
	S_3E_1	297092	11.6	40.2	0.0014	42	0.0934	0.0844	16.61
	S_3E_2	357922	10.9	32.3	0.0013	42	0.0934	0.0844	16.61
	S_3E_3	529907	8.7	15.0	0.0007	46	0.0934	0.0844	16.61
M-W	S_1E_1	1215433	10.9	27.0	0.029	63	0.0227	0.0844	5.71
	S_1E_2	1266544	10.6	23.0	0.024	63	0.0227	0.0844	5.71
	S_1E_3	1444776	9.5	16.0	0.009	67	0.0227	0.0844	5.71
	S_2E_1	158651	8.3	21.9	0.077	22	0.0555	0.0135	16.54
	S_2E_2	209762	8.3	18.0	0.004	24	0.0555	0.0135	16.54
	S_2E_3	387993	7.6	11.3	0.086	29	0.0555	0.0135	16.54
	S_3E_1	272351	9.9	21.7	0.020	42	0.0934	0.0844	16.61
	S_3E_2	323462	9.8	17.7	0.023	42	0.0934	0.0844	16.61
	S_3E_3	501694	9.1	11.0	0.026	46	0.0934	0.0844	16.61

Table 5: Decision variables values for each retrofit alternative in function of the investigated site.

The preferential ranking obtained from each of the retrofit combinations, for each of the locations, is presented in Table 6, together with the relative closeness value. The alternative in position one is considered the most preferred option, and the alternative in position 12 is the least preferred. The relative closeness values range between 0 and 1, with the latter corresponding to the ideal solution, and can be used to understand how strongly one solution is preferred over another. The differences between the various rankings are highlighted in greyscale.

Rank	Medium Hazard						High Hazard					
	Cold climate		Moderate climate		Warm climate		Cold climate		Moderate climate		Warm climate	
	Alt.	Rel. C.	Alt.	Rel. C.	Alt.	Rel. C.	Alt.	Rel. C.	Alt.	Rel. C.	Alt.	Rel. C.
1	S_3E_3	0.676	S_3E_3	0.6761	S_3E_2	0.6551	S_3E_3	0.6572	S_2E_3	0.6290	S_3E_2	0.6334
2	S_3E_2	0.650	S_3E_2	0.6134	S_3E_3	0.6521	S_2E_3	0.6338	S_3E_3	0.6129	S_3E_3	0.6246
3	S_3E_1	0.6034	S_2E_2	0.6042	S_3E_1	0.6361	S_3E_2	0.6319	S_3E_2	0.5925	S_2E_2	0.6212
4	S_2E_3	0.5776	S_2E_3	0.6019	S_2E_1	0.5570	S_3E_1	0.6018	S_2E_2	0.5813	S_3E_1	0.6145
5	S_2E_1	0.5580	S_3E_1	0.5745	S_2E_2	0.549	S_2E_2	0.5992	S_3E_1	0.5738	S_2E_1	0.6110
6	S_2E_2	0.5536	S_2E_1	0.5594	S_2E_3	0.5479	S_2E_1	0.5760	S_2E_1	0.5667	S_2E_3	0.5842
7	S_1E_3	0.4581	S_1E_3	0.3561	S_1E_3	0.4775	S_1E_3	0.3920	S_1E_3	0.4369	S_1E_2	0.4187
8	S_1E_2	0.4388	S_1E_2	0.2483	S_1E_2	0.4260	S_1E_2	0.3395	S_1E_2	0.3972	S_1E_1	0.4172
9	S_1E_1	0.4228	S_1E_1	0.2296	S_1E_1	0.3981	S_1E_1	0.3384	S_1E_1	0.3965	S_1E_3	0.4169

Table 6: Ranking of the retrofit alternatives and respectively relative closeness (Rel.C.) at each location (cold, moderate and warm climate) and for each hazard level: medium (M-H. level) and high (H-H. level).

Across all the investigated sites, the alternatives characterized with S_1 as the structural retrofit are the least preferred, which can be justified by the higher installation cost of this retrofit scheme. Overall, the most preferred structural retrofitting solution is S_3, followed by S_2 with some exceptions. The results for the cold and moderate climate sites (M-C, M-M, H-C and H-M) denote a preference for the alternatives with E_3 energy retrofit scheme, which is justified by the high energy demand on these locations. On the other hand, in general, for the warm sites (M-W and H-W), the seismic retrofit scheme had a more significant effect on the overall ranking than the energy retrofit scheme, since the preferred alternatives are mostly grouped by structural retrofit, with the only exception being S_2E_2 for the H-W. Comparing the ranking obtained between the two different types of seismicity, the preferable interventions oscillate between S_3 and S_2. For the locations with high seismic hazard, C2 is greater for S_2 followed by S_3 and S1 for the cold and moderate climate sites, while for the warm sites, this variable is greater for S_3, followed by S_2 and S_1. This is justified by the higher maintenance cost of intervention S_3 when compared to S_1 and S_2.

5 CONCLUSIONS

The present study investigated the influence of seismic and climatic conditions on the choice of the optimal retrofit solution for a case-study RC school building applying a multi-criteria decision making (MCDM) procedure.

The building was assumed to be located in three sites in Italy of similar medium-to-high (H) seismic hazard levels, with different climatic conditions, respectively characterised by cold (C), moderate (M) and warm (W) climates and, additionally, in three other sites in Italy of similar medium (M) seismic hazard level and, again, with different cold (C), moderate (M) and warm (W) climate conditions. The goal was to perceive the influence of both seismic hazard levels on the choice of the optimal retrofit solution by comparing the ranking obtained for each location as a function of the climate and hazard level.

Regarding the seismic-retrofit interventions, interventions S_1 and S_3, which include, respectively, the reinforcement of structural elements with CFRP and a combination of CFRP and braces, exhibit the best performance. In contrast, intervention S_2, of global nature, presents the worst retrofitted structural performance, regardless of the hazard level. As it was expected, the performance of the retrofitted structure was superior for the locations with moderate (M) hazard level when compared to the locations with high (H) hazard levels. In terms of capacity/demand ratio at SLV, this improvement ranges from 16% to 34% for intervention S_1, 5% to 9% for intervention S_2 and 20% to 90% for intervention S_3. Regarding the energy-retrofit, all the interventions successfully improved the energy performance of the structure, with the biggest improvement being from intervention E_3 to E_1.

The preference rankings obtained from the MCDM framework demonstrated that climate demand significantly impacts the choice of the optimal retrofitting solution, given that the interventions with higher energy performance were preferred for the cold sites, regardless of their higher cost, when compared with the remaining energy retrofit solutions. Across all the investigated sites, the alternatives characterized with S_1 as the structural retrofit are the least preferred, which can be justified by the higher installation cost of this retrofit scheme. The differences in the hazard level conducted slight changes in the ranking, with the preferable interventions varying between S_3 and S_2, which is justified by the oscillating differences in terms of expected annual costs and life-cycle environmental impacts between the two interventions. Overall, given the evident poor seismic performance of the case-study building, the hazard level does not significantly influence the ranking of the alternatives. Consequently, for this building, climate demand had a more meaningful influence on the choice of the optimal retrofitting solution, especially when comparing warmer climates with moderate and cold ones.

ACKNOWLEDGMENTS

The work presented in this paper has been developed within the framework of the projects “ReLUIS 2022-2024”, funded by the Italian Civil Protection Department, and SERENE - 2022.08138.PTDC, funded by the Portuguese Foundation for Science and Technology.

REFERENCES

1. Gkatzogias K, Tsionis G, Romano E, Negro P, Pohoryles D, Bournas D, *et al. Integrated techniques for the seismic strengthening and energy efficiency of existing buildings. Pilot Project Workshop*. 2021. DOI: 10.2760/665617.

2. Menna C, Del Vecchio C, Di Ludovico M, Mauro GM, Ascione F, Prota A. Conceptual design of integrated seismic and energy retrofit interventions. *Journal of Building Engineering* 2021; **38**(January): 102190. DOI: 10.1016/j.jobe.2021.102190.

3. Caruso M, Pinho R, Bianchi F, Cavalieri F. *Integrated economic and environmental building classification and optimal seismic vulnerability / energy efficiency retrofitting*. Springer Netherlands; 2021. DOI: 10.1007/s10518-021-01101-4.

4. Clemett N, Carofilis Gallo WW, Gabbianelli G, O'Reilly GJ, Monteiro R. Optimal Combined Seismic and Energy Efficiency Retrofitting for Existing Buildings in Italy. *Journal of Structural Engineering* 2023; **149**(1): 1–16. DOI: 10.1061/(asce)st.1943-541x.0003500.

5. Carofilis W, Gabbianelli G, Monteiro R. Assessment of Multi-Criteria Evaluation Procedures for Identification of Optimal Seismic Retrofitting Strategies for Existing RC Buildings. *Journal of Earthquake Engineering, In-Press* 2021. DOI: 10.1080/13632469.2021.1878074.

6. Caterino N, Iervolino I, Manfredi G, Cosenza E. Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting. *Computer-Aided Civil and Infrastructure Engineering* 2009; **24**(6): 432–445. DOI: 10.1111/j.1467-8667.2009.00599.x.

7. Saaty TL. The analytic hierarchy process. *New York: McGraw-Hill* 1980.

8. Gallo WWC, Clemett N, Gabbianelli G, O'Reilly G, Monteiro R. Influence of Parameter Uncertainty in Multi-Criteria Decision-Making When Identifying Optimal Retrofitting Strategies for RC Buildings. *Journal of Earthquake Engineering* 2022. DOI: 10.1080/13632469.2022.2087794.

9. Prota A, Di Ludovico M, Vecchio C, Menna C. Progetto DPC-ReLUIS 2019-2021 WP5: Interventi di rapida esecuzione a basso impatto ed integrati 2020; **72**.

10. McKenna F, Scott MH, Fenves GL. Nonlinear Finite-Element Analysis Software Architecture Using Object Composition. *Journal of Computing in Civil Engineering* 2010; **24**(1): 95–107. DOI: 10.1061/(ASCE)CP.1943-5487.0000002.

11. NTC. Norme Technice Per Le Costruzioni 2018.

12. Fajfar P. A Nonlinear Analysis Method for Performance-Based Seismic Design. *Earthquake Spectra* 2000; **16**(3): 573–592. DOI: 10.1193/1.1586128.

13. EDILCLIMA (EDILCLIMA Software and Engineering). EC700 Calcolo Prestazioni Energetiche Degli Edifici—Versione 11. 2021.

14. UNI (Ente Italiano di Normazione). Prestazioni energetiche 11300-1., edifici Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale. 2014.

15. UNI (Ente Italiano di Normazione). Prestazioni energetiche degli edifici Parte 2: Determinazione del fabbisogno di energia primaria per la climatizzazione invernale, per la produzione di acqua calda sanitaria, per la ventilazione e per l'illuminazione in edifici non residenziali 2014.

16. Economico IMDS. *Decreto interministeriale 26 Giugno 2015, Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e*

dei requisiti minimi degli edifici. Rome: Italian Government: 2015.

17. P- F. Guidelines for Performance-Based Seismic Design of Buildings 2018(December).

18. O'Reilly GJ, Sullivan TJ. Quantification of modelling uncertainty in existing Italian RC frames. *Earthquake Engineering and Structural Dynamics* 2018; **47**(4): 1054–1074. DOI: 10.1002/eqe.3005.

19. Calvi GM, Sousa L, Ruggeri C. Energy Efficiency and Seismic Resilience: A Common Approach. *Multi-hazard Approaches to Civil Infrastructure Engineering*, Cham: Springer International Publishing; 2016. DOI: 10.1007/978-3-319-29713-2_9.

20. Mauro G, Menna C, Vitiello U, Asprone D, Ascione F, Bianco N, *et al.* A Multi-Step Approach to Assess the Lifecycle Economic Impact of Seismic Risk on Optimal Energy Retrofit. *Sustainability* 2017; **9**(6): 989. DOI: 10.3390/su9060989.

21. Menna C, Vitiello U, Mauro G, Asprone D, Bianco N, Prota A. Integration of Seismic Risk into Energy Retrofit Optimization Procedures: A Possible Approach Based on Life Cycle Evaluation. *IOP Conference Series: Earth and Environmental Science* 2019; **290**(1): 012022. DOI: 10.1088/1755-1315/290/1/012022.

22. Clemett N, Carofilis Gallo WW, O'Reilly GJ, Gabbianelli G, Monteiro R. Optimal seismic retrofitting of existing buildings considering environmental impact. *Engineering Structures* 2022; **250**(October 2021): 113391. DOI: 10.1016/j.engstruct.2021.113391.

23. Applied Technology Council. Seismic Performance Assessment of Buildings, Volume 1 - Methodology. *Fema P-58-1* 2018; **1**(December 2018): 340.