Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 5362-5375

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

A NEW METHODOLOGY FOR COMBINED SEISMIC AND ENERGY ASSESSMENT OF BUILDINGS

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Abstract

Due to climate change and the increasing CO_2 emissions within the years, the European Union has set up ambitious targets for the decrease of the energy consumption until 2030, promoting funding programs for interventions that increase the energy class of the buildings. In addition, the damage level and the losses after recent earthquake events highlighted the need for pre-earthquake assessment and strengthening of buildings, ensuring life safety and functionality. Several methodologies exist in the literature, proposing seismic classes and a first order prioritization (ranking) system for buildings within an inventory. A second stage assessment is also proposed for the critical buildings of the first ranking, based on risk indexes estimated for selected hazard scenarios and fragility curves. Methodologies and indexes for the combined seismic and energy assessment have also been recently proposed, however, their application is limited to pilot studies and selected inventories. Due to the increased scientific interest on the combined seismic and energy assessment a new methodology has been developed and applied within SURE (Competence Center for Sustainable and Resilient Built Environment). The proposed methodology is based on the fragility curves of buildings and the correlation of seismic hazard with the performance levels (limit states) in order to provide an index indicative of the seismic performance for various levels of earthquake intensity and the relevant damage probability, also proposing weighting factors. The safety index is subsequently combined with an energy efficiency index to provide a holistic approach for the seismic and energy assessment. The energy efficiency index is based on the energy consumption level of buildings and their corresponding classification. The energy-safety bilateral indices provide valuable input to support decision-making systems on renovation strategies of private and public building inventories.

Keywords: seismic assessment, energy assessment, building inventory, performance levels, combined index

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10807.22214

1 INTRODUCTION

In contemporary society, communities are increasingly exposed to natural disasters, highlighting the necessity of building safety. Nevertheless, the majority of existing buildings lack compliance with modern seismic [1] and energy [2] codes and standards, making them susceptible to significant earthquake damage and energy deficiency. This situation results in substantial economic losses, expressed in terms of human casualties, high damage costs, and excessive energy consumption. To address this, preventive measures and retrofitting solutions seem vital. However, until recently, seismic and energy issues have only been handled independently. Contrary to this practice, adopting an integrated holistic approach that combines seismic and energy considerations would provide a more accurate infrastructure performance assessment and successful risk mitigation. More specifically, implementing energy interventions in buildings significantly impacted by earthquakes seems unfeasible, since seismic damage could undermine the effectiveness and economic viability of energy retrofit investments. A comprehensive approach also extends the building lifespan, aligns with sustainable growth policies, reduces energy demand, and minimizes the need for constructing new buildings. Despite prior research efforts in recent years, there is a need for additional investigation into the current issue. This paper represents a further endeavor, aiming at developing a comprehensive combined seismic and energy performance assessment methodology. To address this purpose, seismic and energy efficiency methods are first reported individually, ultimately leading to combined estimation approaches.

The seismic performance evaluation comprises various methods, mainly focusing on probabilistic seismic performance assessment and risk prioritization. Regarding the first, building-based assessment approach, the initial step involves establishing a classification system, aiming at a comprehensive database development [3]. Subsequently, a structural finite element model is compiled and subjected to a seismic intensity measure (IM), linked to the results of the probabilistic seismic hazard analysis. The response output, Engineering Demand Parameter (EDP), captures inter-storey drifts and enables the estimation of building losses. Depending on the research scope and available resources, researchers choose between two main analysis types, Non-Linear Static analysis (NLS) [4] or Non-Linear Dynamic analysis (NLD) [5]. The NLS, also known as pushover analysis, generates capacity curves, which ultimately identify the thresholds of damage states. Given the capacity of the structure, the model is consequently submitted to multiple earthquake intensities, to evaluate the structural seismic performance. The pushover curve is transformed from Force-Displacement to Acceleration-Displacement-Response Spectra (ADRS), utilizing the acceleration-response spectra acquired from seismic records [6]. On the other hand, NLD analysis requires ground motion records for dynamic analysis on a numerical model employing Incremental Dynamic Analysis (IDA) [7]. Both methods produce fragility curves for the predefined damage states, enabling the generation of vulnerability curves by translating physical damage into monetary losses [8]. Combining vulnerability curves with calculated direct loss functions, functionality curves are derived as a percentage of a structure's functionality over time [9]. Ultimately, the Seismic Resilience Index (SRI) can be calculated as the area under the functionality curve, providing a quantitative measure for assessing seismic performance. In some cases, the robustness index is also estimated, a measure that denotes a system's ability to limit the number of failed components and prevent collapse [5]. The alternative approach to evaluating the seismic resilience of buildings involves estimating a risk ranking index. The methodology entails computing a vulnerability index that identifies high-risk buildings based on increasingly detailed filters [10]. Alternatively, a nominal seismic risk index can be estimated based on visual inspection forms for buildings [11]. By encompassing the sum of all infrastructure information, a total building score is calculated, to express the seismic risk class or performance assessment of the infrastructure [12] [13].

Regarding the energy performance assessment, a building categorization of energy classes is developed, expressed in terms of primary energy consumption. Specifically, an energy study is carried out, where a reference building with identical geometric attributes (location, orientation, use) to the inspected one is modeled and is by default categorized as energy class B. Respectively the energy classification of the existing inspected building is estimated as the ratio of primary energy consumption between the existing and reference building. To address this, a specialized energy analysis software, compliant with relevant regulations [14] is utilized. This software incorporates a comprehensive set of building data, encompassing geometric parameters, structural and non-structural components, and thermal characteristics. The primary energy consumption is quantified separately for each end use, both in the existing and the reference building. The resulting energy classification indicates the infrastructure energy efficiency, ranging from A+ (highest achievable energy class) to G (lowest energy class). The classification of the inspected building is determined as the ratio of total primary energy (across all end uses) of the existing (inspected) and reference structure.

However, as already mentioned, no real optimization can be achieved, as a good structural solution could correspond to poor environmental performance and vice versa, highlighting the importance of a combined seismic and energy assessment approach. Most of the modern methodologies, propose an integrated seismic and energy efficiency estimation, expressed in terms of economic parameters, namely cost estimation indices prior to or after retrofitting solutions. More specifically, a comprehensive method initially developed by Romano et al. [15] and later refined by Tornaghi et al. [16], comprises structural and environmental aspects of buildings and summarizes them into a single economic parameter. The SSD (Sustainable Structural Design) approach is based on three main evaluation steps, namely, Energy Performance Assessment, Life-Cycle Assessment, and Structural Performance Assessment. The first two procedures determine the energy consumption and equivalent CO_2 emissions, respectively, while the third one evaluates the building safety performance with respect to structural costs. The final step involves converting the outcomes of the three procedures into economic terms to establish the Global Assessment Parameter of the SSD methodology. Other researchers [17] aim to determine the economic feasibility of the proposed retrofitting alternatives of existing RC structures, in terms of losses. This involves seismic and thermal analyses before and after retrofitting implementation. Economic feasibility is evaluated using the expected annual loss (EAL) measure, which estimates the potential loss in value of the construction over a given period, such as one year. The EAL value is calculated as the sum of two components: the expected annual energy loss (EAL_E), namely the annual energy building consumption multiplied by relative energy cost units, and the expected annual seismic loss (EAL_S).

Notwithstanding the available modern research conducted on this subject so far, there remains a further need for future investigation into the development of an integrated framework that encompasses both seismic risk and energy efficiency of buildings. The present paper aims to address this issue, by employing a new comprehensive consistent approach to existing RC buildings.

2 METHODOLOGY

The proposed methodology identifies the seismic properties of the buildings of the repository. Based on these properties (i.e. structural system, infills, seismic code, regularities,etc.), the buildings are classified and then, the fragility curves are defined according to the database developed by Stefanidou et al. [18]. For every identified building class, the mean of the fragility curves available in the database is calculated at 5 different limit states, namely LS_1: Slight damage, LS_2: Minor damage, LS_3: Moderate damage, LS_4: Major damage, and LS_5: Collapse. For each i-th limit state, an $ag_{,50,i}$ is defined as the horizontal ground acceleration that corresponds to a 50% probability of exceedance of each limit state, according to the respective fragility curve. Each limit state is also matched with a different performance level, i.e., PL_1: Operationality, PL_2: Damage limitation, PL_3: Significant damage, PL_4: Near collapse, and PL_5: Collapse, respectively, which in turn corresponds to a specific return period (T_p). A targeted performance level is selected and the ag of each building site that corresponds to this performance level is defined as the $a_{g,LSi}$, expressing the seismic hazard of the examined building site, following the values of Table 1. The ratio of these two a_g values is the safety factor against the i-th limit state:

$$SF_i = \frac{a_{g,50,i}}{a_{g,LSi}} \tag{1}$$

The prioritization criterion, which is the main outcome of this procedure, is the Structural Performance Index, calculated according to Eq. 2:

$$SPI = \sum_{i=1}^{5} SF_i \cdot W_{PLi} \tag{2}$$

where $W_{PL,i}$ is a user-selected weighting factor for every assessed performance level i, indicating the influence of each performance level on the prioritization of the buildings in terms of the necessity to retrofit. The sum of the weighting factors $\sum_{i=1}^{5} W_{PLi}$ should always be equal to 1. For instance, if the user selects $W_{PL,4} = 1$ and $W_{PL,1} = W_{PL,2} = W_{PL,3} = W_{PL,5} = 0$ for an examined building stock, it is implied that the structural prioritization of the buildings within this stock will be based exclusively on the 'Near Collapse' performance level.

Matching between LS_i (Limit State) / PL_i (Performance Level) and T_p (Return period)					
Building Consequence Class (CC)	T_p years				
	LS: LS1 (Slight) PL: OP (Operationality)	LS: LS2 (Minor) PL: DL(Damage Limitation)	LS: LS3(Moderate) PL: SD (Significant Damage)	LS: LS4 (Major) PL: NC (Near Collapse)	LS: LS5 (Collapse) PL: C (Collapse)
CC1 – Minor importance for public safety	30	50	50	250	800
CC2- Ordinary	**40**	**60**	**60**	**475**	**1600**
CC3a – Important consequences associated with collapse	40	60	60	800	2500

CC3b – Vital importance for civil protection	80	100	100	1600	5000

Table 1 Matching between LS_i / PL_i and T_p

The steps of the proposed methodology are described in the following:
Step 1: Identification of the building repository properties.
Step 2: Classification of the selected buildings according to their structural properties to the classes of the database.
Step 3: Input of the building properties to the fragility curve database.
Step 4: Fragility curves of the selected buildings at 5 limit states (LSi, i = [1,2,3,4,5]).
Step 5: Matching between LSi (Limit State) with the corresponding performance level (PL) and T_p (return period), based on Table 1.
LS1: slight damage, corresponding to the 'operationality' performance level, LS2: minor damage, corresponding to the 'damage limitation' performance level, LS3: moderate damage, corresponding to the 'significant damage' performance level, LS4: major damage, corresponding to the 'near damage' performance level, LS5: collapse, corresponding to the 'collapse' performance level.
Step 6: Calculation of Safety Factor related to every considered i-th limit state: $SF_i = \frac{a_{g,50,i}}{a_{g,LSi}}$

where $\alpha_{g,50,i}$ is the horizontal ground acceleration derived from the fragility curves corresponding to a 50% probability of exceedance of LSi for the examined building, and $\alpha_{g,LSi}$ is the horizontal ground acceleration that expresses the seismic hazard of the examined building site and corresponds to a selected limit state i, according to Table 1.
Step 7: Calculation of SPI (Structural Prioritization Index): $SPI = \sum_{i=1}^{5} SF_i \cdot W_{PLi}$

The building energy assessment begins with the identification of the thermophysical properties and geometrical characteristics of the buildings of the repository and then their primary energy consumption is calculated according to the Greek Regulation on the Energy Performance of Buildings (REPB) [19]. Based on this consumption, the buildings are categorized into the 9 building energy classes that are defined by the classification system of the Greek REPB. In this regulation, the categorization of the buildings is based on the ratio of the primary energy consumption of the examined building over the primary energy consumption of the 'reference building' (Table 2), which is a building unit that is similar to the studied building in terms of geometry, location, orientation, use and operation characteristics, but its technical specifications meet the minimum requirements imposed by the REPB for the construction of new buildings. Other systems that adopt raw values of the primary energy consumption as classification criterion can also be adopted, such as the various regional specifications of the Italian building classification (Table 3). In the presented framework, the categories of the selected classification system are matched to an increasing index, starting from 1 for the lowest energy class (i.e., the class that corresponds to the buildings with the highest primary energy consumption). Last, an Energy Prioritization Index (EPI) corresponding to the building energy class is defined. The steps of the proposed methodology are described concisely in the following:
Step 1: Identification of the building repository properties
Step 2: Calculation of the total primary energy consumption per end use for the selected and reference building
Step 3: Classification of the buildings to energy classes according to their primary energy consumption or the Greek EPB Regulation classification system.

Step 4: Energy Prioritization Index (EPI), corresponding to the building energy class.

Energy Class	Energy Performance
A+	EP < 0.3
A	0.33 < EP < 0.5
B+	0.5 < EP < 0.75
B	0.75 < EP < 1
C	1 < EP < 1.41
D	1.41 < EP < 1.82
E	1.82 < EP < 2.27
F	2.27 < EP < 2.73
G	2.73 < EP

Table 2 Energy classification of buildings depending on the comparison with the reference building [19]

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

Table 3 Energy classification of buildings depending on their primary energy consumption (Italian building classification, regional specification for Emilia-Romagna) [20]

Energy classes derived from the energy analysis categorize the building to the energy prioritization index respectively, indicating the priority order for energy upgrade interventions, as illustrated in Table 4.

Energy Class	Energy Prioritization Index
A+	1
A	2
B+	3
B	4
C	5
D	6
E	7
F	8
G	9

Table 4 Energy class and prioritization index correspondence

Once the seismic and energy prioritization indices are calculated, a comprehensive integrated index is estimated with respect to the priority order required for future seismic and energy retrofit interventions. Three prioritization levels are developed, Low, Medium, and High according to the building seismic and energy assessment respectively. Table 5 and Table 6 depict the corresponding range values for the three levels based on the SPI and EPI index respectively.

Prioritization Level	SPI
Low	>2.5
Medium	1 - 2.5
High	<1

Table 5 Prioritization level – SPI correspondence

Prioritization Level	EPI
Low	1, 2, 3
Medium	4, 5, 6
High	7, 8, 9

Table 6 Prioritization level – EPI correspondence

A 4x4 “color cell” matrix is ultimately developed, demonstrating the priority level order for seismic and energy retrofit interventions respectively, as depicted in Table 7.

	E1 (Low)	E2 (Medium)	E3 (High)
S1 (Low)			
S2 (Medium)			
S3 (High)			

Table 7 Prioritization seismic and energy level

3 CASE STUDY APPLICATIONS

3.1 Description of the buildings

The application of the methodology to selected case studies aims to demonstrate the concept of the herein proposed framework for combined seismic and energy assessment of buildings. For the implementation of the methodology, four distinct RC buildings, located in Greece, are selected, aiming at encompassing a range of structural and energy-related characteristics. The selected buildings differ in terms of their structural system, the year of their construction, the number of storeys, plan, and elevation regularity, and energy classification.

An existing reinforced concrete four-storey apartment building (A) constructed in the Municipality of Kozani in the 1980s, is first considered. It's a moment-resisting frame with plan and elevation regularity. Prior to any energy retrofitting interventions, the total primary energy consumption categorizes the structure as energy class F. The second selected building (B), as illustrated in Fig. 1., is a 1980s two-storey residential building in Kozani respectively, characterized by a moment-resisting frame with shear walls and energy classification G according to energy performance.

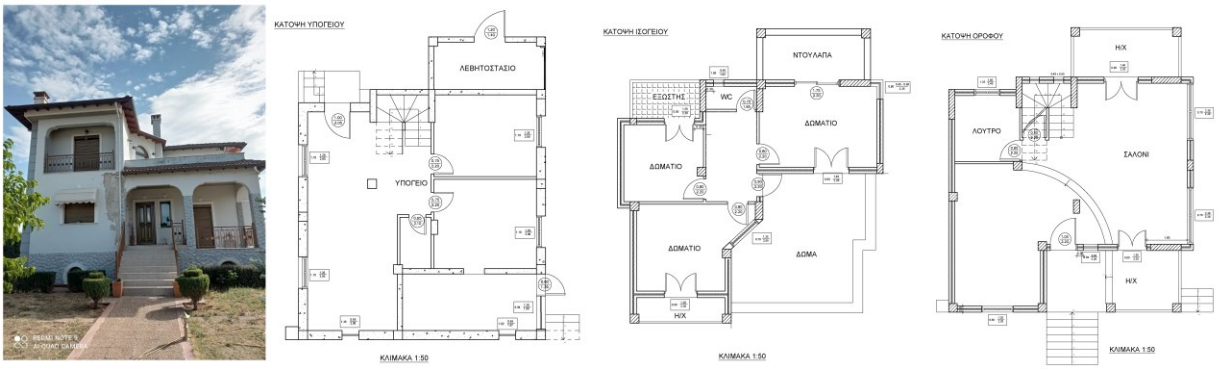

Figure 1 Photograph and plan view of building B in Kozani

The two remaining selected buildings are both located in the Municipality of Thessaloniki, one constructed prior to 1959 while the other in the 1980s respectively. Specifically, a single-storey residential building (C) is studied, plan, and elevation regular with a force-resisting frame as structural system. Based on its primary energy consumption is classified as energy category G. Fig. 2 depicts a 1980s five-storey apartment (D) with pilotis in Thessaloniki respectively. It employs a moment-resisting frame and is categorized as energy class E.

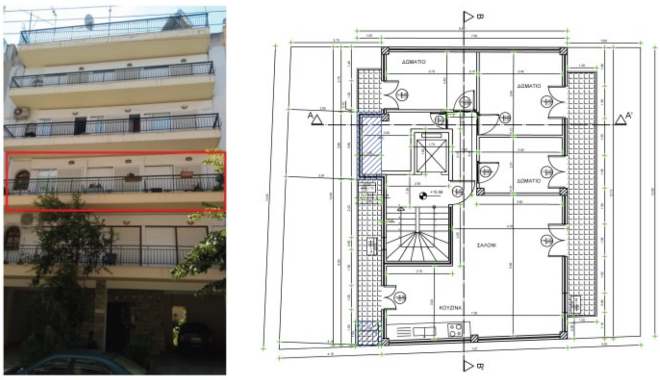

Figure 2: Photograph and plan view of building D in Thessaloniki

Table 8 provides a cumulative overview of the seismic and energy properties of the building classification, required for the application of the proposed methodology.

Building	Properties							
	Force Resisting Mechanism	Height Level	Code Level	Intensity Measure	Plan/ Elevation Regularity	Infill	Ductility	Energy class
A	Moment-Resisting Frame	Mid Rise (4-7)	Low Code	PGA	Regular/ Regular	Regular Infill	Non-Ductile	F
B	Moment-Resisting Frame with shear Walls	Low Rise (1-3)	Non-Code	PGA	Irregular/ Irregular	Regular Infill	Non-Ductile	G
C	Moment-Resisting Frame	Low Rise (1-3)	Low Code	PGA	Regular/ Regular	Regular Infill	Non-Ductile	G
D	Moment-Resisting Frame	Mid Rise (4-7)	Low Code	PGA	Regular/ Regular	Irregular Infill	Non-Ductile	E

Table 8 Building Taxonomy

3.2 Application of the methodology proposed

Once the building taxonomy is established, the methodology proposes individually estimating the seismic and energy prioritization index. A cloud fragility database [18] is employed, containing the available in literature fragility curves. Fragility curves for five predefined limit states are extracted, by utilizing the structural building properties as search criteria. To estimate the Structural Prioritization Index (SPI), the seismic hazard is to be initially assessed, using the European Seismic Hazard Model 2020 (ESHM20) [21] through the EFEHR web platform, a network aiming at earthquake hazard and risk assessment in the European-Mediterranean region. The hazard curve development includes selecting the location of interest based on the geographical coordinates for each of the four selected buildings. Subsequently, the hazard model for a relevant intensity measure (in the present paper peak ground accelerations are utilized) are determined. Finally, the site class and aggregation type are specified. Fig. 3 illustrates the hazard curve for building C, indicating the probability of exceedance of the selected seismic action over a 50-year period.

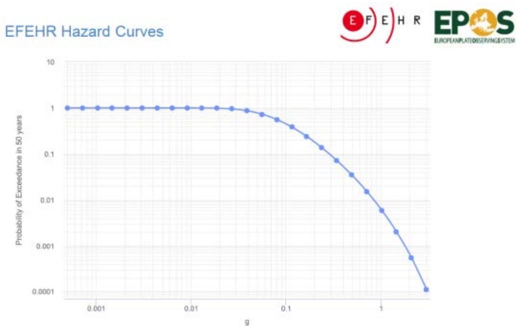

Figure 3 Hazard curve of building C

Table 9 summarizes the horizontal ground acceleration $a_{g,\,LSi}$ estimated from the generated hazard curves of all four buildings, expressing the seismic hazard of the examined building corresponding to the selected limit states.

Building	$a_{g,LSi}$ (m/s^2)				
	LS1 (Slight)	LS2 (Minor)	LS3 (Moderate)	LS4 (Major)	LS5 (Collapse)
	T_P years (CC2)				
	40	60	60	475	1600
A	0.049	0.066	0.066	0.223	0.397
B	0.052	0.069	0.069	0.227	0.380
C	0.058	0.078	0.078	0.279	0.511
D	0.058	0.078	0.078	0.270	0.490

Table 9 $a_{g,LSi}$ values overview

Aligning with the steps outlined in the methodology section, the horizontal ground acceleration $a_{g,50,i.}$ is derived from the generated mean fragility curves, as depicted in Fig. 4, corresponding to a 50% probability of exceedance for each limit state of the selected buildings. Table 10 provides a comprehensive overview of the horizontal ground acceleration values, a prerequisite measure for the Safety Factor assessment.

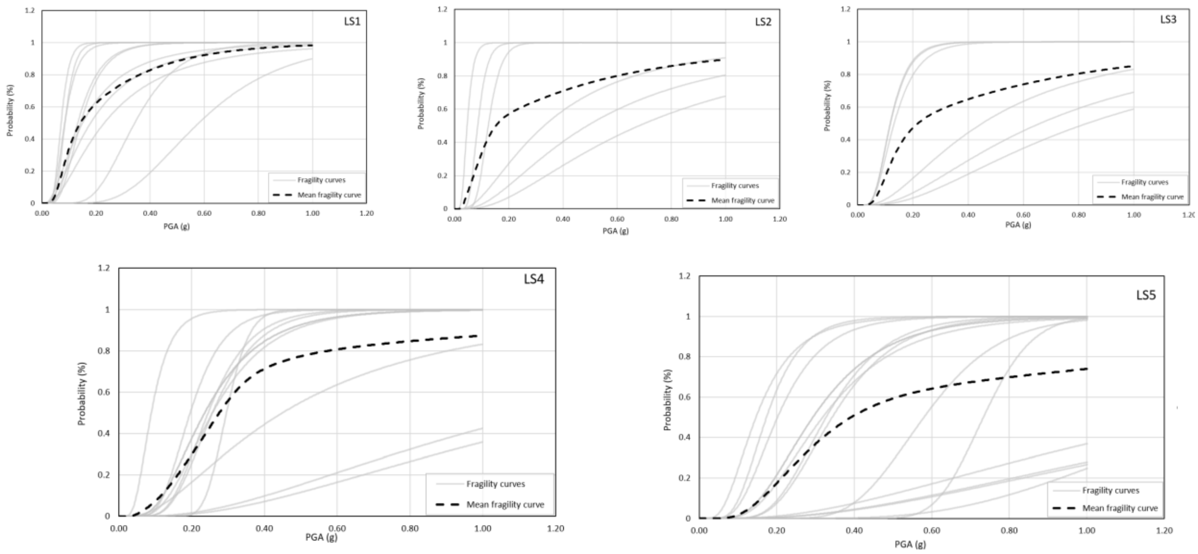

Figure 4 Mean and fragility curves for the five limit states

Building	$a_{g,50,i}$ (m/s^2)				
	LS1 (Slight)	LS2 (Minor)	LS3 (Moderate)	LS4 (Major)	LS5 (Collapse)
A	0.021	0.090	0.199	0.218	0.311
B	0.070	0.280	0.464	0.618	0.850
C	0.142	0.152	0.217	0.276	0.391
D	0.020	0.021	0.083	0.117	0.283

Table 10 $a_{g,50,i}$ values overview

The Safety Factor index estimation is ultimately established as the ratio of horizontal ground accelerations $a_{g,50,i}$ and $a_{g,LSi}$, as depicted in Table 11. The Structural Prioritization Index (SPI) is then derived by multiplying the safety factor values for all limit states of the selected buildings with user-selecting weighting factors W_{LSi} for each performance level, highlighting the influence of Limit State 4, representative of design earthquake with a return period of 475 years.

Building	SFi					Wi					SPI
	LS1	LS2	LS3	LS4	LS5	LS1	LS2	LS3	LS4	LS5	
A	0.429	1.364	3.015	0.978	0.783	0.125	0.125	0.125	0.50	0.125	1.19
B	1.346	4.058	6.725	2.722	2.237	0.125	0.125	0.125	0.50	0.125	3.16
C	2.448	1.949	2.782	0.989	0.765	0.125	0.125	0.125	0.50	0.125	1.49
D	0.345	0.269	1.064	0.433	0.578	0.125	0.125	0.125	0.50	0.125	0.50

Table 11 Structural Performance Index assessment

The present framework proposes the Energy Prioritization Index (EPI) assessment as the ratio of the primary energy consumption of the selected, existing building to the reference one. The energy analysis TEE KENAK software [14] was employed to estimate the primary energy consumption per end-use, encompassing all building parameters, namely geometric data, thermophysical properties of structural elements, and technical characteristics of the HVAC systems. Energy classes derived from the energy analysis categorize the building to the energy prioritization index respectively, indicating the priority order for energy upgrade interventions (see Table 4). Table 12 describes the Energy Prioritization Index (EPI) assessment for the four selected buildings, corresponding to the estimated energy classes.

Building	Inspected building Total primary energy consumption (kWh/m^2)	Reference building Total primary energy consumption (kWh/m^2)	Energy Class	EPI
A	316.3	128.6	F	8
B	491.2	177.0	G	9
C	1041.7	183.6	G	9
D	335	174.3	E	7

Table 12 Energy Performance Index assessment

The four selected buildings considered in this case study are classified into three different levels (Low, Medium, High) according to their priority order for future seismic and energy interventions. Table 13 presents the prioritization level categorization based on Tables 5 and 6 for the seismic and energy indices respectively, applied for the set of the four buildings, as illustrated in Table 14.

Building	SPI Level	EPI Level
A	S2 (Medium)	E3 (High)
B	S1 (Low)	E3 (High)
C	S2 (Medium)	E3 (High)
D	S3 (High)	E3 (High)

Table 13 Prioritization SPI and EPI levels

	E1 (Low)	E2 (Medium)	E3 (High)
S1 (Low)			Building B
S2 (Medium)			Building A, C
S3 (High)			Building D

Table 14 Prioritization seismic and energy level for the selected buildings

4 CONCLUSIONS

The individually studied seismic and energy performance assessment of the existing RC buildings in modern literature, highlights the necessity of a comprehensive, integrated approach development. Despite the recent attempts of a combined seismic and energy efficiency investigation, parameters as performance levels and their weighting factors are usually overlooked in common practice. To address this gap, the present study encompasses five performance levels for a selected seismic hazard parameter, described by user-selected weighting factors with a primary focus on the design earthquake for a return period of 475 years. The applicability of the proposed methodology is examined through its implementation to four existing buildings with a minimal set of required parameters, namely a building classification system, hazard definition, and fragility data repository [18]. A qualitative index of three levels is ultimately developed, indicating the prioritization order for further seismic and energy upgrade and retrofit interventions. However, future research would undoubtedly enhance knowledge about this relatively new subject of integrating building design.

5 AKNOWLEDGEMENT

This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme "Competitiveness Enterpreneurship Innovation 2014-2020" in the action «Competence Centers» in the context of the project "Competence Center for a Sustainable and Resilient Built Environment using smart technologies" (MIS 5130744).

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