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Review

The Seismic Evaluation of Existing Buildings for Energy Renovation—A Case Study for the Residential Building Stock in Bucharest (Romania)

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Abstract: This study focuses on an overview of two programs applied to the residential building stock of Bucharest (Romania), namely, the seismic strengthening program and the thermal rehabilitation program. The methodology for seismic risk assessment given in the current generation of Romanian codes, as well as in previous regulations, is examined. A brief review of other seismic risk assessment methodologies currently applied in various seismically prone countries is also presented. Examples of high-rise buildings in Bucharest that suffered significant damage during the Vrancea 1977 earthquake and that were thermally rehabilitated without any strengthening works are shown in this paper. The consistent differences between the current outcomes of the two programs are presented and discussed. Finally, this review paper highlights the lack of coherence in terms of seismic risk assessments for the same class of buildings, inducing, in some situations, a false feeling of safety in the building inhabitants. In addition, a combined procedure for both seismic strengthening and thermal rehabilitation is mandatory, considering the seismicity of Romania, as well as ongoing climate change.

Keywords: seismic design codes; Vrancea earthquakes; high-rise buildings; seismic assessment; seismic risk class; thermal rehabilitation

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1. Introduction

This paper focuses on a discussion related to the seismic strengthening of existing buildings in the context of the current EU energy renovation programs, with an emphasis on the residential building stock of Bucharest. Currently, most of the population in Bucharest inhabits low-rise or high-rise buildings constructed in the period 1956–1990. From the point of view of energy renovation, it is clear that all of these buildings need rehabilitation in order to reduce energy consumption. From the point of view of seismic risk, a significant proportion of these buildings were affected by the Vrancea 1977 earthquake. The works in the aftermath of the 1977 earthquake were mainly repair works aimed at recovering the initial lateral load capacity. Thus, in order to have a complete image of the issue discussed in this paper, the results of the seismic strengthening program of residential buildings in Bucharest are also discussed. Unfortunately, for various reasons, which are presented in this study, energy efficiency rehabilitation was not coupled with the necessary strengthening works. To better understand this issue, a detailed review of the current methodologies for seismic risk assessment in Romania is also presented in this study. Finally, a brief discussion and comparison of other procedures for the seismic assessment of existing buildings applied in various seismically prone countries are also beneficial in the context of this review.

In the context of the topic of this paper, it has to be mentioned that both seismic strengthening and thermal rehabilitation should be combined into a single strategy aimed at increasing the safety of existing buildings and reducing energy consumption. Thus, the study by Caruso et al. [1] proposes a life-cycle framework for the identification of the optimal renovation strategy for buildings. This approach is based on the quantification of the economic and environmental contributions of multiple building life-cycle stages considering the additional effects of earthquake-induced damage and repair activities, as well. Lamperti Tornaghi et al. [2] proposed a sustainable structural design (SSD) method considering both environmental and structural parameters in life-cycle assessment. Manfredi and Masi [3] propose an integrated approach for the design of interventions able to simultaneously provide thermal and seismic rehabilitation for buildings in Italy. A combined strategy aimed at improving both the seismic performance and energy efficiency based on a life-cycle assessment was proposed in the study by Clemett et al. [4]. Other methodologies aimed at combining both the seismic and energy criteria can be found in [5–7]. A review of the methods for the combined assessment of seismic resilience and energy efficiency toward the sustainable retrofitting of existing European buildings can be found in the studies by Menna et al. [8] or Ademovic et al. [9]. Moscella et al. [10] show a case study for the energy and seismic rehabilitation of two historical buildings in Italy. Martiradonna et al. [11] present a solution for improving both the seismic and energetic performance of reinforced concrete buildings by using precast concrete panels. Various other structural solutions proposed for the same purpose include CLT panels [12,13], textile-reinforced mortars [14], RC-framed skins [15], waste materials [16] and sandwich panels [17]. Besen and Boarin [18] studied the same issue with application to heritage buildings with unreinforced masonry structures in New Zealand. A non-invasive solution aimed at improving both the seismic performance and energy efficiency criteria for historical buildings in Italy is presented in the paper by Negro et al. [19]. A review of various solutions for improving both seismic performance and energy consumption for Italy and Romania is discussed in the study by Georgescu et al. [20]. The study by Pohoryles et al. [21] shows that in areas with moderate and high levels of seismic hazard (as is the case of Bucharest), the largest part of the expected annual loss reductions is due to seismic retrofitting. The assessment of the integrated seismic and energy retrofitting of European buildings [22] illustrated that Romania is one of the priority regions that can benefit from an integrated seismic and energy retrofitting approach.

The main objectives of this study are as follows:

- A historical review of the seismic risk assessment methodologies applied in Romania;
- A review of seismic risk assessment methodologies in other seismically prone countries in the world;
- A comparison of the outcomes of seismic strengthening and thermal rehabilitation programs for the residential building stock of Bucharest.

2. A Brief Evaluation of the Residential Building Stock of Bucharest

For the reader to properly evaluate and understand the issues discussed in this paper, a brief description and evaluation of the residential building stock of Bucharest are provided below based on the data collected during the 2011 census. More detailed information on the residential building stock of Bucharest can be found in other studies in the literature (e.g., [23,24]). The main observations regarding the residential building stock of Bucharest are as follows:

- A total of 60% of the entire existing building stock of Bucharest was built before 1970.
- About 20% of the population inhabits buildings with fewer than three stories.
- Most of the structures in Bucharest have masonry structures (more than 50%), while more than 10% of the buildings in Bucharest have adobe structures.
- Out of about 132,000 buildings, about 6000 have more than nine stories in height and house about 50% of the population of Bucharest.
- About 2500 high-rise buildings with more than nine stories were built before 1977, and the same number was built in the period 1978–1990. All of them were affected by at least one major Vrancea intermediate-depth earthquake (in 1977, 1986 or 1990).

- Another 20% of the residential population of Bucharest lives in about 2800 five-story buildings, 60% of which were built before 1977.

Thus, based on the above-mentioned observations, it is clear that the targets of seismic strengthening and thermal rehabilitation programs are quite limited (about 5% of the existing building stock). The majority of the target buildings were constructed based on typified designs; thus, the construction details in a particular period are rather similar for all buildings constructed in that particular period, rendering such buildings suitable for a general technical assessment (for a particular building type).

3. Methodology for Seismic Risk Assessment of Buildings in Romania

3.1. Brief History of Seismic Risk Methodologies in Romania

Seismic risk assessment and seismic strengthening generally become important issues after major seismic events that generate considerable losses. In the case of Romania, this situation applies to the last two major Vrancea intermediate-depth earthquakes of 1940 and 1977. However, the first official methodology for the seismic risk assessment of existing buildings was adopted after 1990, as part of the design code P100-92 [25]. Only in 2008, with the adoption of the code P100-3/2008 [26], was the seismic design of new buildings separated from the seismic assessment of existing buildings. Finally, the most recent version of the code for the seismic risk assessment of existing buildings was adopted in 2019 (P100-3/2019 [27]). A comparison of various parameters of the methodologies applied in the above-mentioned design codes is shown in Table 1.

Table 1. Comparison of code-based seismic risk assessment methodologies applied in Romania.

Code	Period of Application	Mean Return Period of Seismic Action (Years)	Methods of Analysis	Material Strengths	Risk/Vulnerability Index	No. of Seismic Risk/Vulnerability Classes
P100-92 [25]	1992–1996	50	Linear/nonlinear	Design values	$R = S_{cap}/S_{req}$	3
Update of P100-92 [25]	1997–2008	50	Linear/nonlinear	Design values	$R = S_{cap}/S_{req}$	4
P100-3/2008 [26]	2009–2019	100	Linear/nonlinear	Mean value/($CF*SF$)	Indicators R_1, R_2 and R_3	4
P100-3/2019 [27]	2020–	225	Linear/nonlinear	Mean value/CF for ductile elements Mean value/($CF*SF$) for brittle elements	Indicators R_1, R_2 and R_3	4

In Table 1, *CF* is the confidence factor (which is a function of the knowledge level), *SF* is the safety factor, which depends on the material, and S_{cap} and S_{req} are the seismic capacity and demand, respectively. It can be observed in Table 1 that a single limit state (life safety) is employed for seismic risk calculations in all versions of the methodologies employed in Romania. In addition, the mean return period used for the risk assessment of existing structures has gradually increased from 50 years to 225 years. An important aspect that has to be highlighted is the fact that the adoption of the latest version of the code for the seismic risk assessment (in 2020) of existing structures took place seven years after the adoption of the most recent version of the seismic design code for new structures (the code P100-1/2013 [28]). In the first two versions of the seismic risk assessment methodology in 1992 and 1996, the risk classes for buildings were called urgency classes. The minimum values of the risk/vulnerability index necessary for structural interventions are shown in Table 2 for the four codes applied in Romania as a function of the importance/exposure class of the building. Table 3 shows the correlations between the values of the risk indicators R_1, R_2 and R_3 and the seismic risk classes for the P100-3/2008 [26] and P100-3/2019 [27] codes.

Table 2. Minimum values of risk/vulnerability indexes necessary for structural interventions as a function of the importance/exposure class.

Code	**Minimum Value of Risk/Vulnerability Index for Structural Interventions**			
	Class 1	**Class 2**	**Class 3**	**Class 4**
P100-92 [25]	<0.70	≤0.30 for class U_1 ≤0.60 for class U_2	≤0.15 for class U_1 ≤0.25 for class U_2 ≤0.35 for class U_2	-
Update of P100-92 [25]	0.70	0.60	0.50	0.50
P100-3/2008 [26]	R_3 < 0.65 (or 0.75 for sites affected by Banat earthquakes)			
P100-3/2019 [27]	For all buildings having seismic risk classes 1 and 2			

Table 3. Correlations between the values of the risk indicators and the seismic risk classes for the P100-3/2008 [26] and P100-3/2019 [27] codes.

Code	**Risk Indicator**	**Seismic Risk Class**			
		Class 1	**Class 2**	**Class 3**	**Class 4**
P100-3/2008 [26]	R_1	<30	30–60	61–90	91–100
	R_2	<40	40–70	71–90	91–100
	R_3	<35	36–65	66–90	91–100
P100-3/2019 [27]	R_1	<30	30–59	60–89	90–100
	R_2	<50	50–69	70–89	90–100
	R_3	<30	30–59	60–89	90–100

In Table 1, R_1 is an indicator quantifying the way in which the seismic construction requirements are fulfilled, the indicator R_2 evaluates the current damage level of the building, and R_3 quantifies the seismic strength and ductility of the building for the code seismic demand (corresponding to the ultimate limit state).

The 1992 version of the code [25] included a relation for the evaluation of the maximum remaining lifetime of a building based on the value of the risk index R:

$$T_{exp}{}^{max} = 100\ R^2, \tag{1}$$

Finally, it has to be highlighted that Rel. (1) was proposed previously in the late 1980s in a study by Georgescu and Sandi [29].

3.2. Current Approach to Seismic Risk Assessment of Buildings in Romania

As previously mentioned, the seismic risk assessment of existing buildings in Romania is performed based on the P100-3/2019 code [27]. Both the current version of the seismic assessment code, as well as its previous version from 2008, have a number of similarities to Eurocode 8-3 [30]. Besides this code, another document, C254-2017 [31], most recently updated in 2022, is also employed as a basis for the seismic risk assessment of residential buildings in Bucharest for thermal rehabilitation purposes.

The current procedure for seismic risk assessment from the P100-3 generation of codes divides buildings into four risk classes (the proper term should be vulnerability classes)—risk class I (the highest risk level) to risk class IV (the lowest risk level). A building with risk class IV is similar to a new building designed according to the current code generation. Moreover, it has to be mentioned that the risk assessment is performed with respect to the seismic demand computed in accordance with the design code enforced at that moment. Thus, the code P100-3/2019 [10] makes reference to the seismic zonation map from the code P100-1/2013 [28], while the previous version from 2008 made reference to the zonation map from the code P100-1/2006 [32]. As previously mentioned, there is a clear difference between the two zonation maps from 2006 and 2013, in the sense that the mean return period of the design peak ground acceleration has increased from 100 years to 225 years.

For Bucharest, the design peak ground acceleration, which is used as a reference for seismic risk assessment, has increased from 0.24 g to 0.30 g. The control period T_C of the design response spectrum is 1.6 s in both seismic design codes, while the maximum spectral acceleration (corresponding to the constant spectral acceleration plateau) has increased from 0.66 g (in the 2006 version of the code) to 0.75 g (in the 2013 version of the code). The code describes a seismic risk class III building as one that will experience moderate damage during the design ground motion, while a seismic risk class II building will suffer extensive damage (structural and non-structural), which might jeopardize the safety of the users, but a total or local collapse is unlikely.

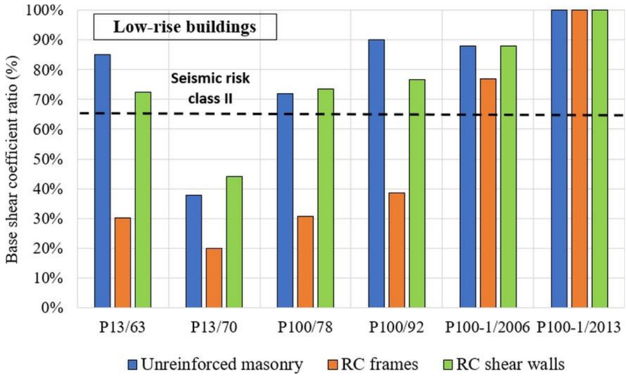
To evaluate the R3 indicator, three separate methodologies (with different and increasing complexity levels) can be used. The level III methodology makes use of nonlinear analyses (static or dynamic), but it is seldom used since it requires a large amount of information about the building.

Except for situations in which the state of the building is extremely poor (which is not the case for residential buildings in Bucharest), the seismic risk class is basically the minimum between the values of the R1 and R3 indicators.

Both versions of the P100-3 code stated that structural interventions are necessary for buildings classified as having seismic risk class I or II. Thus, in order to perform thermal rehabilitation without structural interventions for strengthening purposes, the building has to be classified as having seismic risk class III.

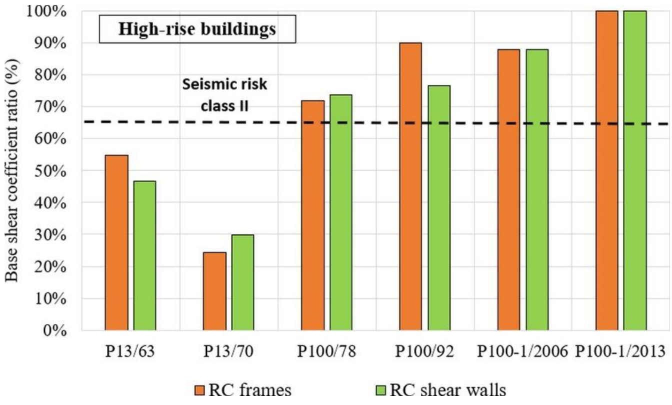
In the case of the R1 indicator, it is basically computed by considering four criteria: (1) the structural configuration (45% contribution), (2) the structural interactions, (3) the structural system (30% contribution) and (4) the slabs. The combined contribution of the structural configuration and the structural system accounts for 75% of the value of the R1 indicator. Except for flexible stories, which can occur in soft-story structures (constructed in the late 1950s along some of the main boulevards in Bucharest), and the material quality (only found in the 2019 version of the code), there are no reasons for penalizing buildings built in the period 1956–1977. These structures can be penalized based on structural system criteria since they do not follow the requirements given in modern design codes. As such, a simple computation leads to a value of the R1 indicator of about 0.70–0.80 for reinforced concrete (RC) shear wall structures built in the period 1956–1977.

The ratios between the design base shear coefficients for various structural systems corresponding to buildings built considering various seismic codes (P13-63 [33], P13-70 [19], P100-81 [34], P100-92 [25], P100-1/2006 [32] and P100-1/2013 [28]) for Bucharest are illustrated in Figure 1. Unconfined masonry walls, RC frames and RC shear walls are considered structural systems for low-rise buildings, with the latter two being employed for high-rise buildings, as well. It has to be emphasized that unreinforced masonry structures with five stories have not been allowed to be constructed in Bucharest since the mid-1970s, as a height limitation was imposed on this structural typology.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. Ratios between base shear coefficients as a function of the seismic design code and structural system for (**a**) low-rise buildings; (**b**) high-rise buildings.

It can be observed in Figure 1 that the smallest ratios between the base shear coefficients for new buildings and for older ones are for those constructed in the period of application of the P13-70 code [19]. For some structures (e.g., RC frames, high-rise RC shear walls), the ratio is below 0.35, corresponding to seismic risk class I.

It has to be further emphasized that the checks for the R3 indicator are performed considering an increased level of design seismic action. For instance, the behavior factor considered when evaluating the design value for an RC shear-wall structure is in the range 2–4, depending on the period of construction and accounting for significant uncertainties in terms of information about reinforcement ratios, details, etc.

Considering the previous discussion about the value of the R1 indicator and the base shear coefficient ratios shown in Figure 1, it is clear that, for buildings constructed in the period 1956–1977, the seismic risk class is given by the R3 indicator.

Detailed seismic risk assessments of high-rise buildings built before 1977, which are similar to the ones that collapsed during the major Vrancea intermediate-depth earthquake of 4 March 1977 (moment magnitude M_W = 7.4 and focal depth h = 94 km), can be found in the studies by Pavel and Carale [35] and Pavel and Vacareanu [36]. In the case of both above-mentioned structures, a change in the seismic risk class has occurred over time, in the sense that the seismic risk class initially evaluated by a technical expert was later decreased. This situation has been observed for a number of buildings in Bucharest, even though their vulnerabilities were documented in the aftermath of the Vrancea 1977 intermediate-depth earthquake [37]. For instance, some OD-section-type buildings (one of the structures commonly built before 1977 in Bucharest) [36,38] were initially evaluated as having seismic risk class II, which was later modified through subsequent technical expertise to seismic risk class III. It has to be further stressed that the mean return period of a seismic event having a similar magnitude to that of the 1977 event is much shorter (e.g., less than 50 years), corresponding more to the serviceability limit state (as defined in the P100-1/2013 [28] code).

4. Methodologies for Seismic Risk Assessment in Design Codes

In the context of the detailed discussion shown in the previous section regarding the seismic risk assessment methodology applied in Romania, a brief review of other methodologies applied in seismically prone countries in the world can also provide the reader with relevant information. It is important to add that, currently, a significant number of procedures for evaluating the seismic risk (in terms of losses) for structures can be found in the literature.

A description of the Italian guide"Ines'for the seismic risk classification of constructions approved in 2017 can be found in the study by Cosenza et al. [39]. The seismic risk class of a building is defined as the minimum between two classes, one associated with a safety index (computed as a ratio between the demand and the capacity peak ground acceleration) of the structure at the life safety limit state (LS-LS) and the other related to the expected annual losses (EALs) obtained for ground motion levels with different return periods. Thus, it is clear that a much more complex seismic risk assessment is applied in Italy compared with the current approach in Romania.

In the case of New Zealand, the 2016 Building (Earthquake-prone Buildings) Amendment [40] identifies an earthquake-prone building as one that has a rating smaller than 34% of that corresponding to a new building. The limit imposed in New Zealand is similar to the one for seismic risk class I from the P100-3 series of codes applied in Romania.ASCE 41-23 [41] is the most recent version of the code for the seismic evaluation and retrofitting of existing buildings in the United States. The approach in ASCE 41-23 [41] distinguishes between structural and non-structural performance objectives. Another important reference for the seismic risk assessment of existing buildings is the Standard for Seismic Evaluation developed by the Japan Building Disaster Prevention Association [42].

Some key parameters related to the above-mentioned seismic risk assessment methodologies are briefly summarized in Table 4.

Table 4. Comparison of seismic risk assessment methodologies applied in various countries or codes.

Country/Code	Mean Return Period of Seismic Action (Years)	Methods of Analysis	Material Strength	Risk/Vulnerability Index	No. of Seismic Risk/Vulnerability Classes
Italy	475	Linear/nonlinear	Mean value/(*CF***SF*)	Min (*SI-LS*, *EAL*)	7 for *SI-LS* and 8 for *EAL*
New Zealand	475	Linear/nonlinear	Probable values (larger than characteristic values)	D/C	6
United States	225, 975, 2/3*values for MCE_R	Linear/nonlinear	Values obtained from testing or design documents. For linear analyses, a confidence factor is employed, as well.	Acceptance ratio (D/C)	4
Japan	0.6 or 0.8 of the design value for a new building	Linear	Specified design strength	$I_s/I_{so} = E_o \cdot S_D \cdot T / I_{so}$	-
Eurocode 8/3	225, 475 or 2475	Linear/nonlinear	Mean value/(*CF***SF*)	D/C	-

In Table 4, MCE_R represents the maximum considered earthquake, E_0 is the basic seismic index of the structure, S_D is the irregularity index, T is the time index, D represents the seismic demand, C is the seismic capacity, CF is the confidence factor (which is a function of the knowledge level) and SF is the safety factor. The risk/vulnerability index is evaluated at the element level, and its final value for a particular structure is considered the minimum one determined previously.

In Table 4, it can be observed that the Italian guidelines for seismic risk classification of constructions are the only regulation that proposes a probabilistic seismic risk format, with the other approaches basically evaluating the seismic risk for a single given ground motion amplitude.

Another important issue regarding the various seismic risk methodologies discussed previously is the different approaches in terms of material strength, leading to significant differences between assessments. In this context, it is important to note that the future Eurocode 8-3 [43] will remove the confidence factors from the assessment of material strength.

The seismic performance objectives considered in the seismic risk assessment methodologies discussed in this section are briefly given in Table 5. It can be observed that single-limit-state or multi-limit-state approaches are employed as well for seismic risk assessments in the analyzed codes.

Table 5. Comparison of the seismic performance objectives from seismic risk assessment methodologies applied in various countries or codes.

Country/Code	Structural Seismic Performance Objectives	Non-Structural Seismic Performance Objectives
Italy	4, from operational to collapse	-
New Zealand	Life safety	-
United States	5, from immediate occupancy (S-1) to collapse prevention (S-5)	4, from operational (N-A) to hazards reduced (N-D)
Japan	Life safety	-
Eurocode 8/3	3 (Near Collapse, Significant Damage and Damage Limitation)	-

5. Case Study—Residential Building Stock of Bucharest

In this section, the results of two programs applied to the residential building stock of Bucharest, namely, the seismic strengthening program and the thermal rehabilitation program, are discussed.

5.1. Seismic Strengthening Program in Bucharest

The most recent statistics from the Municipal Administration for the strengthening of buildings with seismic risk (https://amccrs-pmb.ro/lista-imobile-2/, accessed on 8 May 2024) show that about 110 buildings of various heights have been strengthened in the past 30 years. Out of the 110 strengthened buildings, only 11 are more than nine stories in height, and, with one exception, all of them were constructed before 1950. It has to be emphasized that there were other programs (e.g., World Bank-financed) in which some public buildings (e.g., schools) were strengthened, as well.

The main Issues that have limited the efficiency of this program were mainly related to the necessary documents (ownership issues) that had to be prepared by each individual resident of a building; the costs of the strengthening works, which, in some situations, had to be paid by the residents (albeit over a significant number of years); or the need to temporarily move to different locations due to the construction works (there were situations in which the temporary move lasted for several years). The decision to proceed with strengthening works is to be made by most of the owners in a building, but the legal procedures for those who do not agree are quite complicated. Moreover, with strengthening works, a decrease in the interior spaces of apartments is likely to occur (due to the increased size of the structural elements), and, in some situations, a rearrangement of the entire space can occur. Generally, structural interventions along the façades (of older buildings) are complicated to approve due to cultural heritage issues; thus, structural interventions are generally concentrated in the interior parts of the buildings.

5.2. Thermal Rehabilitation Program in Bucharest

The data regarding the thermal rehabilitation program for residential buildings in Bucharest, obtained from https://www.reabilitaretermica.eu/ (accessed on 11 March 2024) and from data made public by other local institutions in Bucharest at the district level, show that a total number of more than 4000 buildings (blocks of flats) have been thermally retrofitted to date. This number is more than 40 times larger than the total number of strengthened buildings. In order to be eligible for thermal rehabilitation, the seismic risk class of the buildings should be III or IV. Buildings in seismic risk class II are allowed only if the structural interventions are finished. It has to be emphasized again that, for seismic risk class II buildings, according to the definition given in the code P100-3 [27], major structural damage is expected (and non-structural damage, as well). Thus, the condition for thermally retrofitting only buildings having seismic risk classes III and IV is obvious.

As shown by various public sources, the thermal rehabilitation program will continue in subsequent years with funding from the National Project for Recovery and Resilience, with the same limitations regarding the seismic risk classes of buildings.

From the point of view of structural systems employed for residential buildings in Bucharest, as well as in other major cities in Romania, masonry structures were employed for low-rise buildings mainly before 1970 [44]. Large panel structures were subsequently employed for most of the low-rise buildings constructed until 1990. In the case of the high-rise structures, cast-in-place RC shear walls were used before 1977, while afterward, the majority of the high-rise structures were also made using large panels [44]. It has to be emphasized that even in the case of the cast-in-place RC shear walls built after 1977, the façade is, in most situations, made of prefabricated non-load-bearing elements that do not fulfill the current thermal insulation requirements.

However, below, we document several instances in which vulnerable buildings in Bucharest (which suffered significant damage during the Vrancea 1977 earthquake) have been thermally retrofitted without any structural strengthening.

An example of a soft-story structure thermally retrofitted and for which the strengthening works performed after the Vrancea 1977 are still visible is shown in Figure 2.

Figure 2. A soft-story structure that was heavily damaged during the Vrancea 1977 earthquake and that was recently thermally retrofitted without additional structural interventions.

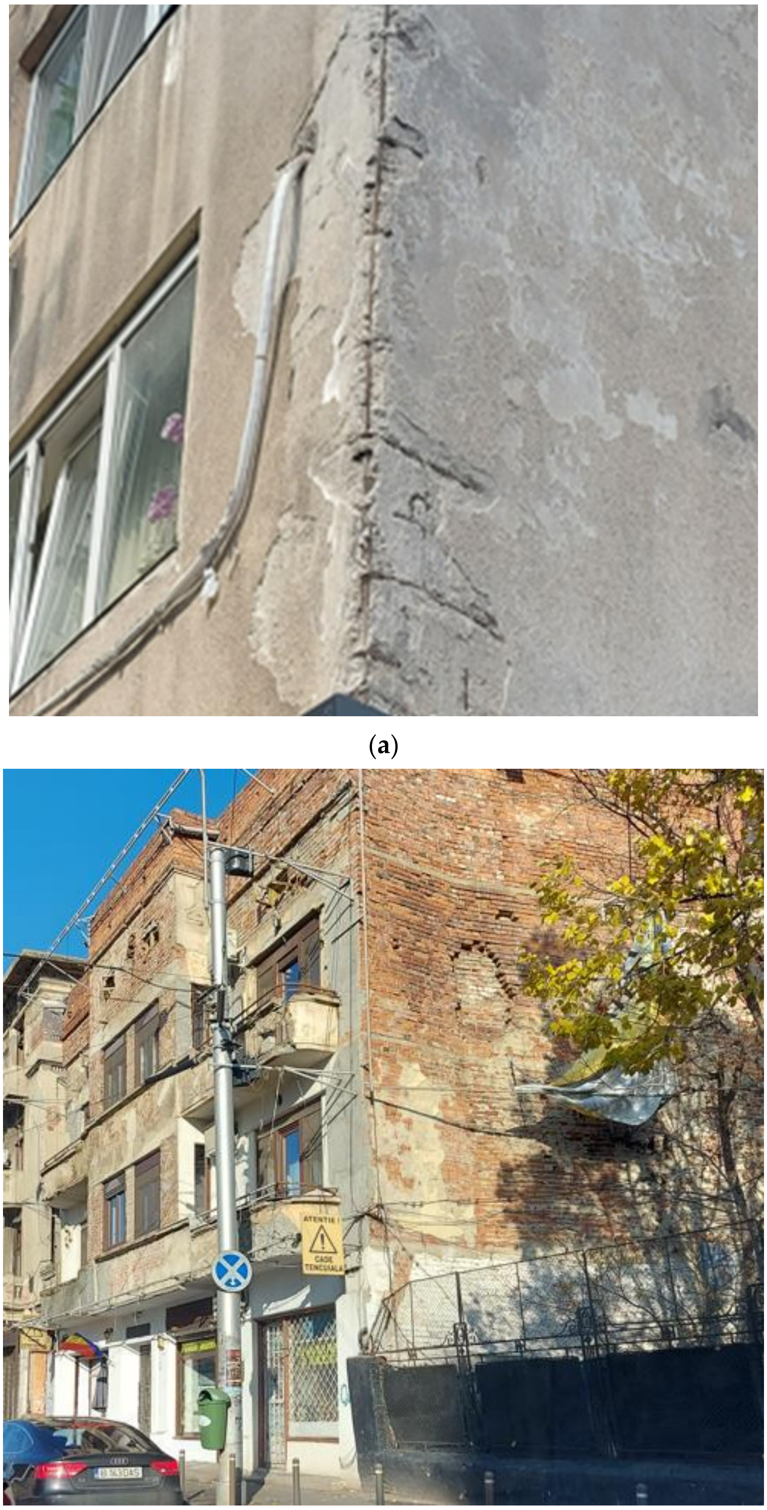
Two other examples of buildings with a similar structural system that were recently thermally retrofitted are shown in Figure 3.

Various solutions that ensure both seismic strengthening and thermal rehabilitation have been given by various researchers in the literature (e.g., [3,45–49]). The recent study by Penazzato et al. [50] consists of a valuable literature review on this topic focusing on materials and solutions for integrated seismic and energy rehabilitation. A proper adaptation of such solutions considering the structural typologies commonly encountered in Romania should be sought as soon as possible in order to decrease the seismic risk of residential buildings in Bucharest. The current state of various buildings in Bucharest (both low-rise and high-rise) is shown in Figure 4, highlighting the need for both seismic strengthening and thermal rehabilitation.

(**a**)

(**b**)

Figure 3. (**a**,**b**) Buildings that were damaged during the Vrancea 1977 earthquake and that were thermally retrofitted without structural interventions.



(**a**)

(**b**)

Figure 4. *Cont.*

(**c**)

(**d**)

Figure 4. The current state of various existing buildings in Bucharest: (**a**) the expulsion of the concrete cover; (**b**,**c**) the falling of plaster; (**d**) roof damage and chimney collapse.

6. Conclusions

This review paper presents a discussion related to the seismic strengthening of existing buildings, with a case study dealing with the residential building stock of Bucharest (Romania). A discussion regarding the procedure of seismic risk assessment given in the current generation of Romanian codes is also presented, as well as a brief historical evolution of these methodologies. In addition, the seismic risk assessment approaches in various codes in various seismically prone countries in the world are briefly summarized and discussed. Finally, a comparison regarding the current outcomes of the thermal rehabilitation program and the seismic strengthening program for residential buildings in Bucharest is also discussed, with an emphasis on the role of seismic risk assessment. The main observations based on the analyses performed for this research can be summarized as follows:

1. Studies in the literature have shown that Romania (including Bucharest) is among the regions in Europe that can benefit from an integrated seismic and energy retrofitting approach.
2. The majority of the current seismic risk assessment methodologies in the world involve an assessment for a single ground motion level (limit state). The Italian guidelines for the seismic risk classification of constructions approved in 2017 [39] involve a proper probabilistic seismic risk assessment.
3. A major source of differences in terms of seismic risk assessments performed using the various methodologies shown in this study is the material strength. Design, probable or mean values are prescribed in the various approaches, thus leading to nonuniform risk results.
4. There is a net and clear difference regarding the number of strengthened residential buildings in Bucharest and the number of buildings that were thermally retrofitted. The number of thermally retrofitted buildings is more than 40 times larger than the total number of strengthened buildings.
5. The situations in Bucharest in which a seismic risk class was decreased are observed even for buildings that suffered moderate and extensive damage during the Vrancea intermediate-depth earthquake of 1977 (which has a much smaller return period than the design one). The assignment of a seismic risk class lower than the one based on the real behavior of a particular structure, as observed from the observations made in the aftermath of the Vrancea 1977 intermediate-depth earthquake, might induce a false level of safety in the residents of that building.
6. It is obvious that by increasing the seismic demand (based on the design seismic action), the gap between a building built using past codes and a new code will increase. Thus, the scale of the seismic strengthening issue at the national level will become larger and larger. As a solution, other performance objectives (less stringent) should be allowed as measures to increase the number of strengthened buildings. Moreover, the limits between the different seismic risk classes should be adjusted in order to consider changes in the design ground motion levels.

The main observation in this review study is that there is no combined approach for performing thermal rehabilitation and seismic strengthening in Bucharest. It appears, based on the information from this study, that the solution that has been applied in many instances in Bucharest was to just simply assign a lower seismic risk class to buildings such that they will be eligible for the thermal rehabilitation program (which was conducted by a technical expert). The case of buildings that were documented as suffering extensive damage during the Vrancea 1977 earthquake (which has a much smaller return period than that corresponding to the design ground motion used for seismic risk assessment) and that were thermally retrofitted without any seismic strengthening is noteworthy. Unfortunately, the various repairs or local strengthening applied to some buildings after the Vrancea 1977 earthquake has not been properly documented in the various documents necessary for the thermal rehabilitation program. Finally, based on the current state of various buildings in Bucharest (and in the rest of Romania, as well), combined with the seismicity of Romania and ongoing climate change, it appears that there is an urgent need for both seismic strengthening and thermal rehabilitation.

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