Journal of Architectural Sciences and Applications
JASA 2023, 8 (Special Issue), 355-377
Research article
e-ISSN: 2548-0170
https://dergipark.org.tr/en/pub/mbud

Investigation of Energy Efficient and Earthquake Resistant Rehabilitation Methods in Existing Residential Buildings

Seher GÜZELÇOBAN MAYUK [1], Rana UZUN [2]*, Merve ÖZDOĞAN [3]
Betül ALANKUŞ [4], Ali Kemal YILDIRIM [5]

ORCID 1: 0000-0002-2676-4784 **ORCID 2:** 0000-0001-9414-0175 **ORCID 3:** 0000-0002-6643-1749
ORCID 4: 0000-0002-7272-0811 **ORCID 5:** 0009-0000-6562-9131

[1-2-3-4] *Gebze Technical University, Faculty of Architecture, Department of Architecture, 41400, Kocaeli, Türkiye.*
[5] *Gebze Technical University, Institute of Natural and Applied Sciences, Department of Architecture, 41400, Kocaeli, Türkiye.*
**** e-mail**: rkamiloglu@gtu.edu.tr*

Abstract

Many studies are carried out in the rehabilitation of existing residential buildings, addressing the energy released during the pre-construction, construction, use and demolition stages of the building and circularity. Furthermore, in Türkiye, earthquakes are one of the primary influencers impacting the lifespan of buildings. However, a limited number of studies take a holistic approach, integrating both energy efficiency and earthquake resistance in existing residential buildings. To promote awareness on the subject, it is aimed to systematically examine the rehabilitation methods in reinforced concrete residential buildings. Seven studies were reviewed through literature analysis to investigate structural strengthening methods, energy efficient improvement techniques and their costs. The studies concluded that rehabilitation and strengthening were carried out in the structure and different building elements, and energy costs were reduced. Based on the data obtained, the steps to be followed in rehabilitating the residential buildings in this context were determined.

Keywords: *Sustainability, circularity, energy-efficient rehabilitation, seismic resilient rehabilitation, rehabilitation of existing residential buildings.*

Mevcut Konut Yapılarında Enerji Etkin ve Depreme Dayanıklı İyileştirme Yöntemlerinin İncelenmesi

Öz

Günümüzde mevcut konut yapılarının iyileştirilmesinde yapının inşa öncesi, inşa süreci, kullanım ve yıkım aşamalarında açığa çıkan enerji ve döngüselliği ele alan birçok çalışma yapılmaktadır. Ayrıca depremler Türkiye'de yapının yaşam sürecini etkileyen en önemli faktörlerdendir. Çalışma kapsamında mevcut konut yapılarının enerji etkin ve depreme dayanıklı olarak bütüncül bir yaklaşımla iyileştirilmesini ele alan araştırma sayısının sınırlı olduğu tespit edilmiştir. Konu hakkında farkındalığın artırılması amacıyla betonarme konut yapılarında ilgili iyileştirme yöntemlerinin sistematik olarak incelenmesi hedeflenmiştir. Literatür taraması yöntemiyle erişilen yedi araştırmada ele alınan yapılar; yapısal güçlendirme yöntemleri, enerji etkin iyileştirme yöntemleri ve yöntemlerin maliyeti açısından irdelenmiştir. Yapılan araştırmalarda konutun taşıyıcı sistem ve farklı yapı elemanlarında iyileştirme-güçlendirmelerin gerçekleştirildiği, kullanılan yöntemlerle enerji maliyetlerinde azalma olduğu sonucuna erişilmiştir. Elde edilen veriler doğrultusunda konutların bu doğrultuda iyileştirilmesinde izlenecek adımlar belirlenmiştir.

Anahtar kelimeler: *Sürdürülebilirlik, döngüsellik, enerji etkin iyileştirme, depreme dayanıklı iyileştirme, mevcut konutların iyileştirilmesi.*

Citation: Güzelçoban Mayuk, S., Uzun, R., Özdoğan, M., Alankuş, B. & Yıldırım, A. K. (2023). Investigation of energy efficient and earthquake resistant rehabilitation methods in existing residential buildings. *Journal of Architectural Sciences and Applications*, 8 (Special Issue), 355-377.
DOI: https://doi.org/10.30785/mbud.1332267

Received: *27/07/2023* – ***Accepted:*** *02/12/2023*

1. Introduction

Today different criteria play a role in the design process of residential buildings in the discipline of architecture. With the impact of global warming and climate change, which has reached to an alarming level, energy efficiency in residential buildings has become important than ever. In addition, earthquake-resistant building design plays an equal role due to the devastating effects of earthquakes on buildings and users caused by the constant movement of the earth's crust. Since newly built residential buildings increase global energy consumption even more, choosing to improve earthquake resistance while ensuring energy efficiency in the existing housing stock stands out as a more economical, sustainable and circular approach. In the national and international literature, there are studies in which energy-efficient rehabilitation and earthquake-resistant (structural) rehabilitation for existing residential buildings are addressed separately. However, the number of studies examining the two approaches together is limited. Therefore, it is necessary to understand energy, circularity, earthquake effects, energy-efficient and earthquake-resistant rehabilitation methods of residential buildings in detail.

1.1. Energy, Energy Efficiency of Buildings, Sustainability and Circularity

The concept of energy is briefly defined as the work capacity of a system and has an important place for people in all areas of life (*What Is Energy?*, 2022). With the Industrial Revolution that started at the end of the 1700s, energy sources consisting of fossil fuels began to be consumed rapidly and the increase in the amount of greenhouse gases such as carbon dioxide released into the atmosphere resulted in the emergence of the concepts ‘global warming’ and ‘climate change’. In 1975, the term global warming was first used, but it gained more popularity after being used by NASA climate scientist James Hansen, in his testimony before the U.S. Senate in 1988. Since the 2000s, its usage has increased, largely due to climate change (Lineman et al., 2015). With the global warming and climate change crisis, resource consumption of buildings, waste management and control of the environmental effects have gained importance. In this context, the consumption of renewable resources such as hydroelectricity, biomass, biofuels, wind, geothermal and solar energy that do not harm natural cycles has been encouraged and studies have begun to limit the use of non-renewable resources such as petroleum and petroleum products, gasoline, diesel, heating oil, natural gas, coal, hydrocarbon gas liquids, and nuclear energy. Furthermore, countries all around the globe organized various conferences and meetings on climate change and global warming and formed public opinion on the subject as seen in Figure 1.

With the Paris Agreement signed in 2015, stakeholder countries have pledged to work to keep global warming at +2.5 ^{o}C on a global scale and to make progress in their countries with new regulations in this regard. In the Intergovernmental Panel on Climate Change held in 2018 the following issues were raised (Kabbej Sofia, 2017):

- The necessity of reducing the global warming level below +1.5^{o}C,
- Reduction of greenhouse gas emissions by 45% in 2030 compared to 2010, and zeroing in 2050,
- Important strategies in agriculture, energy, industry, transportation and construction sectors,
- Minimizing or even stopping the use of fossil fuels and using completely renewable energy sources.

Türkiye, which meets its energy needs largely through imports (TPAO, 2022), signed the Paris Agreement in 2021 and has accelerated its work on the subject in recent years. With various regulations and auxiliary resources such as the Green Deal Action Plan (T.C. Ticaret Bakanlığı, 2021) and the Guidebook for Nearly-Zero Energy Buildings (nZEB) (T.C. Çevre ve Şehircilik Bakanlığı, 2020). It has started to raise awareness of both the public and people from energy-related sectors.

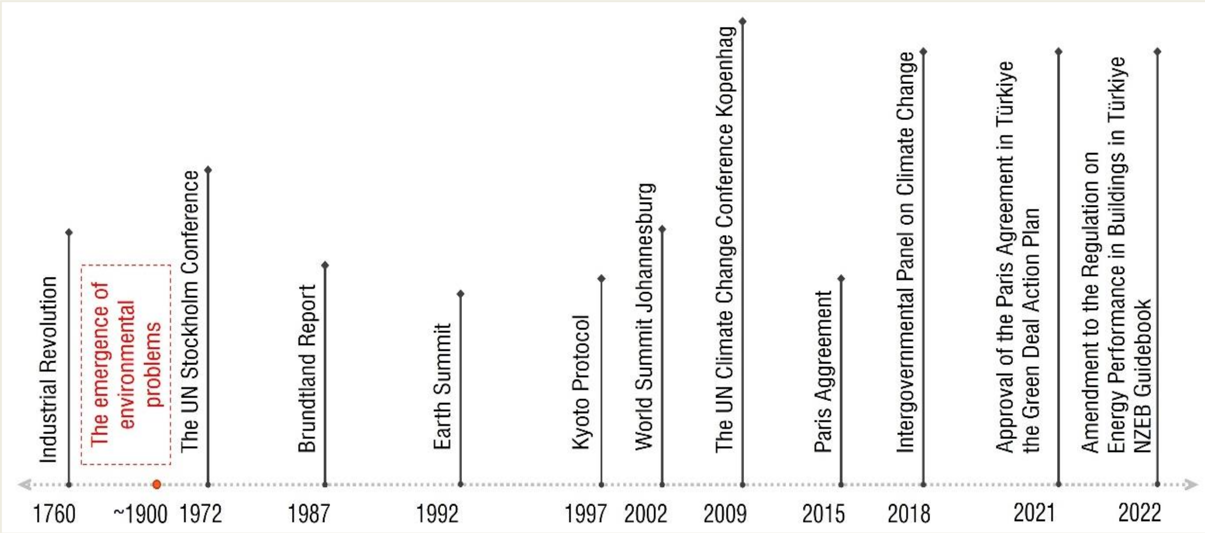

Figure 1. Chronological order of meetings on climate change and global warming

After the Paris Agreement, various research was conducted on the distribution of energy consumption of sectors on a global scale. Global Alliance for Buildings and Construction, a voluntary organization supported by the UN Environment Program since 2016, documents the distribution of the industry on energy consumption and carbon emissions with The Global Status Report for Buildings and Construction, which it publishes every year. When the impact of the building construction industry on global energy consumption and carbon emission is analyzed in line with the published reports, it is seen that it has a share of approximately 35-40% between the years 2016-2022. According to the latest report published in 2022, the share of the building construction sector in energy consumption is 37%, and its share in carbon dioxide emissions is 34%. According to the same report, the impact of residential buildings on energy consumption directly (direct consumption due to production activity) and indirectly (consumption in the background of production activity) is higher than non-residential buildings. It is aimed to reduce this rate according to the 'Net Zero Emission' targets for 2050 (International Energy Agency, 2021). From this point of view, the amount of energy consumed and carbon released before and during construction (embodied energy/carbon), during the use of the building (operational energy/carbon), and demolition phases for each new residential building is of global importance. In this context, it is seen as a more environmentally friendly and economical solution to increase user comfort and safety by making some rehabilitation so that existing residential buildings can complete their life spans in a healthier way, instead of constantly building new ones. This solution also supports the concepts of sustainability and circularity, which countries have emphasized in recent years to use their resources more efficiently.

The concept of sustainability first emerged in the 1980s and there are many definitions of the concept developed with the same purpose and different approaches. The most comprehensive and frequently used definition of this subject is known as the definition made by the Bruntland Commission in 1987 (Tufan & Özel, 2018). According to the aforementioned definition, sustainability is defined as meeting the needs of today's people without compromising the vital needs of future generations (Kılınçarslan et al., 2019). The sustainability approach is based on the principles of protecting and maintaining ecology. This approach suggests that it is beneficial to use renewable, eco-friendly, economical, and healthy products instead of depleted non-renewable resources.

When sustainable approaches are examined, the concept of ‘Circularity’ (also called ‘Circular Economy (CE)’) which is based on economic and environmental effects, comes to the fore (Dabaieh et al., 2022). The concept of circularity, which is based on the reduction of harmful environmental effects and economic los.

s in the life cycle of a building, has been frequently discussed in recent years. Circularity is based on the approach of reducing the environmental footprint of different industries (Eberhardt et al., 2022).

The reduction in environmental footprint is seen as a solution to reach a sustainable future. In addition, the circularity approach aims to increase welfare by reducing the need for energy and primary materials (Deselnicu et al., 2018).

Circularity consists of several steps to ensure efficient use of materials and products. In the literature, the concept of circularity is generally evaluated under five main headings: refurbish, remanufacture, reuse, repair, and recycle (Zhang et al., 2021). Potting et al. (2017), developed basic principles called 'R-strategies' by taking the concept of circularity more comprehensively in their studies. R-strategies are discussed in 10 basic principles with the titles of narrowing, slowing, and closing the cycle of materials and products as seen in Table 1 (Potting et al., 2017).

Table 1. Circularity principles (Potting et al., 2017)

Smarter product use and manufacture	R0	Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	Rethink	Make product use more intensive (e.g., through sharing products, or by putting multi-functional products on the market)
	R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3	Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	Repair	Repair and maintenance of defective product so it can be used with its original function
	R5	Refurbish	Restore an old product and bring it up to date
	R6	Remanufacture	Use parts of discarded product in a new product with the same function
	R7	Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	Recover	Incineration of materials with energy recovery

Within the scope of circularity in buildings, when these principles are taken as reference in the pre-construction, construction process, use and demolition stage the ecosystem cycle is completed successfully. In the pre-construction design phase, the cycle can be narrowed by the principles of refuse (R0), rethink (R1) and reduce (R2). The life cycle of the products can be extended by providing re-use (R3), repair (R4), refurbish (R5), remanufacture (R6) and repurpose (R7) during the building use phase and with these the life cycle of the building can be slowed down. In the demolishing phase of the building life cycle, resources can rejoin the cycle by using the principles of recycle (R8) and recover (R9). The cycle is completed with this approach, which uses materials, products, and energy effectively. Circularity not only saves on materials, products and energy but also reduces dependency on countries in resource supply and employment (Ellen Macarthur Foundation, 2013).

Another parameter that affects building construction activities and building life cycle is the ‘earthquake’ reality. Earthquakes are among the most destructive natural disasters in the world and have caused serious loss of life and property throughout history. Today, it is possible to reduce the destructive effects of earthquakes and prevent loss of life and property by understanding the reality and effects of earthquakes and then taking various precautions in buildings.

1.2. Earthquakes and Their Effects

As a result of the division of the Earth's crust into tectonic plates, these plates move continuously and slowly on the Earth's surface for millions of years, causing stresses in the Earth's crust over time. When the stresses increase in size, the resulting stress energy causes the movement of cracks called faults. Sudden movements that occur on the fault line because of tectonic movements are called 'earthquakes' (NASA, 2021). Therefore, an earthquake can be defined as the ground shaking or movement caused by the breaking and displacement of the deep layers in the earth's crust (Türk Dil Kurumu (TDK), 2023).

Earthquakes are one of the most destructive natural disasters in the world. Earthquakes have caused loss of life and material damage in different geographies throughout history. Depending on the measures taken by the countries against earthquakes, these damage levels can be reduced. The 10 major earthquakes that have caused the greatest loss of life in the world in the last 100 years are summarized in Table 2.

Table 2. Major earthquakes of the world in the historical process (edited from Austin, 2015; USGS, 2019; Wikipedia, 2023)

Date	Location	Magnitude	Loss of Life
1.09.1923	Japan	7.9-8.2	142.800
22.05.1960	Chile	9.5	1.665
28.03.1964	Alaska	9.2	128
26.01.2001	India	7.7	20.085
29.12.2004	Indonesia	9.1	227.898
8.10.2005	Pakistan	7.6	87.351
12.05.2008	China	7.9	87.587
12.01.2010	Haiti	7.0	160.000
11.03.2011	Japan	9.0-9.1	19.000
25.04.2015	Nepal	7.8	8.964

The earthquakes in Table 2 are listed from past to present. The information about the location where the earthquakes took place, the magnitude of the earthquakes and the loss of life are given. When the data is examined, it is seen that the largest earthquake in terms of magnitude was the 9.5 earthquake that took place in Chile in 1960. On the other hand, the earthquake with the highest loss of life with 227,898 people is the 9.1 magnitude earthquake that took place in Indonesia in 2004. In this sense, it is seen that magnitude and loss of life are not directly proportional, and various factors (such as population and building quality) may be effective in the number of casualties. Türkiye is in the Mediterranean-Alpine-Himalayan seismic belt, where one-fifth of the earthquakes in the world are experienced. This seismic belt, which is one of the most influential earthquake belts in the world, covers 93% of Türkiye’s land (TMMOB, 2010).

Due to its location, Türkiye is among the countries with high earthquake risk and activity in the world. For this reason, earthquakes have occurred in Türkiye since the early ages, causing great loss of life and property (Ceylan, 2004). The major earthquakes that took place in Türkiye in recent years are given in Table 3. The location where the earthquakes took place, the size, the loss of life and the number of heavily damaged residential buildings determined because of the earthquakes are given chronologically. In Table 3, it is seen that the biggest earthquake was the Erzincan earthquake with a magnitude of 7.9 in 1939, while the number of casualties and heavily damaged residential buildings were mostly seen in the Kahramanmaraş earthquakes in 2023.

Table 3. Major earthquakes of Türkiye in the historical process (edited from Altun, 2018; Henley, 2023; Bikçe, 2015; Wikipedia, 2023)

Date	Location	Magnitude	Loss of Life	Heavily Damaged Residential Building Number
6.05.1930	Hakkari Border	7.2	2.518	3.000
26.12.1939	Erzincan	7.9	32.962	116.720
20.12.1942	Tokat-Niksar	7	3.000	32.000
26.11.1943	Kastamonu-Tosya	7.2	2.824	25.000
1.02.1944	Bolu-Gerede	7.2	3.959	20.865
28.03.1970	Gediz	7.2	1.086	19.291
30.10.1983	Erzurum-Kars	6.8	1.155	3.241
17.08.1999	Kocaeli-Gölcük	7.4	18.374	93.618
23.10.2011	Van	7.2	644	38.515
6.02.2023	Kahramanmaraş-Pazarcık	7.7	59.259	227.027
6.02.2023	Kahramanmaraş-Elbistan	7.6		

Various mistakes made in the design, construction and use stages of the buildings may cause the buildings to be damaged more than expected during an earthquake, such as (Gülmez, 2010):

- Reinforcing steel placement errors,
- Insufficient details at the junction of column-beam regions,
- Soft floors created on the ground floors of buildings,
- Spaces without infill walls,
- Consoles arranged in accordance with regulations,
- Damage or destruction of load-bearing elements,
- Irregularity in the horizontal or vertical plane of the structure.

Different levels of damage can occur in buildings after an earthquake. In determining the damage levels, buildings can be classified as 'undamaged', 'slightly damaged', 'moderately damaged', 'heavily damaged' and 'in urgent need of demolition'. Undamaged buildings are buildings that have not been damaged by earthquakes. Slightly damaged buildings are buildings where thin cracks are seen on the walls, paint, and plaster of the building as a result of the earthquake. There is no harm in using undamaged and slightly damaged buildings. In moderately damaged buildings, thin cracks in the load-bearing elements and cracks in the walls can be seen. The building cannot be used unless the damage to the building is repaired. It can be determined that there are separations and breaks in the load-bearing due to earthquakes in heavily damaged buildings. Due to the loss of bearing capacity the buildings cannot be used. In buildings to be demolished urgently, the load bearing elements of the building are completely or partially collapsed. Therefore, the building cannot be used or entered (ÇŞİDB, 2023).

According to the 2021 population and city census, there are 40.200.000 residential buildings in Türkiye (TÜİK, 2022). It is seen that 47.4% of these buildings were built in 2001 and after. It is understood that this rate is 45.7% in Istanbul, which is slightly below the Türkiye average (Table 4).

Table 4. Number and proportion of residential buildings according to the construction year of the building (TÜİK, 2022)

Provinces	Number of residential buildings	Construction year of the building				Construction year of the building (%)				
		1980 and before	1981-2000	2001 and after	Unknown	Total	1980 & before	1981-2000	2001 & after	Unknown
Total	25.329.833	3.179.805	7.834.588	12.007.355	2.308.085	100.0	12.6	30.9	47.4	9.1
İstanbul	4.755.086	493.276	1.750.833	2.173.468	337.508	100.0	10.4	36.8	45.7	7.1

Kahramanmaraş Province Pazarcık and Elbistan district earthquakes, which occurred in Türkiye in 2023 and are shown as one of the most destructive earthquakes in world history, affected a very wide geography covering 11 cities, including the Mediterranean, Southeastern Anatolia and Eastern Anatolia regions. 14.05% of Türkiye's total housing stock is in these provinces in the earthquake zone (Table 5). 5.649.317 buildings in the regions were severely damaged by the earthquake. Apart from the destruction of the buildings, the earthquakes also caused damage to the superstructure and infrastructure of the regions and brought the economic and commercial activities in the regions to a standstill.

Table 5. Number of residences in provinces affected by Kahramanmaraş earthquakes, 2021 (T.C. Cumhurbaşkanlığı Strateji ve Bütçe Başkanlığı, 2023)

Province	Number of Residential Buildings
Adana	972.561
Adıyaman	216.744
Diyarbakır	563.295
Elazığ	292.406
Gaziantep	893.558
Hatay	847.380
Kahramanmaraş	481.362
Kilis	74.976
Malatya	345.536
Osmaniye	243.436
Şanlıurfa	718.063
Total of Region	5.649.317
Türkiye	40.200.000

When the ratio of households living in the building stock of 11 provinces after the earthquake is examined, the ratio of living in buildings constructed in 1980 and before is 12.6% in Türkiye, while it is 10% in the earthquake zone. In terms of this rate Adana, Hatay and Kilis are above the Türkiye average. While the rate of households living in houses built between 1981 and 2000 is 30.9% for the country in general, the average of 11 provinces affected by the earthquake is 27.6%. In terms of the ratio of households residing in buildings built in 2001 and after, Türkiye's average is 47.4%, while the earthquake zone average is 51.1% while Adana, Hatay, Kilis and Osmaniye are below the Türkiye average. According to Table 6, it is understood that the building stock in Adana, Hatay and Kilis is relatively old (T.C. Cumhurbaşkanlığı Strateji ve Bütçe Başkanlığı, 2023).

Earthquake codes have been revised eight times in total, including 1947, 1953, 1961, 1968, 1975, 1998, 2007 and 2018 (still in use) in Türkiye. In this respect, it cannot be said that all buildings built before 2000 are risky, and it cannot be said that all buildings built after 2000 are safe. In general, it is known that buildings built before 2000 are less resistant to earthquakes, and buildings built after 2000 are more secure against earthquakes (T.C. İçişleri Bakanlığı Afet ve Acil Durum Yönetimi Başkanlığı, 2022). The fact that the existing building stock in Türkiye is not ready for earthquakes can be seen in the examinations after the Pazarcık and Elbistan earthquakes, as in the past earthquakes. Almost all the casualties in earthquakes in Türkiye are due to damage and collapse of buildings. For this reason, the most important step in reducing earthquake damages is to make existing buildings safe against earthquakes and to construct new buildings to be earthquake resistant (T.C. Cumhurbaşkanlığı Strateji ve Bütçe Başkanlığı, 2023).

In this context, the strengthening, repair, and renovations to be made in the buildings with slight and moderate damage after the earthquake are of urgency. These improvements are important because they contribute to less energy consumption in residential buildings while protecting against earthquakes. In earthquake-prone countries, seismic rehabilitation methods need to be integrated into sustainable rehabilitation strategies. Technical solutions that combine both also contribute positively to the country economy in terms of building investment return and more savings (Di Vece & Pampanin, 2019).

Table 6. Household ratio according to the construction year of the building in the provinces affected by the Kahramanmaraş earthquakes, 2021 (T.C. Cumhurbaşkanlığı Strateji ve Bütçe Başkanlığı, 2023)

Province	Building Construction Year (%)			
	1980 & before	1981-2000	2001 & after	Unknown
Adana	13,0	34,8	38,7	13,5
Adıyaman	8,7	23,6	52,3	15,4
Diyarbakır	6,5	26,6	58,1	8,8
Elazığ	10,0	23,6	52,8	13,6
Gaziantep	6,6	25,9	51,6	15,9
Hatay	13,5	32,6	50,0	3,9
Malatya	11,7	26,9	58,1	3,3
Kahramanmaraş	11,2	21,7	52,3	14,9
Kilis	14,0	28,1	48,4	9,5
Osmaniye	10,5	25,7	46,5	17,3
Şanlıurfa	5,5	18,5	61,0	14,9
Total of Region	10,0	27,6	51,1	11,3
Türkiye	12,6	30,9	47,4	9,1

1.3. Building Rehabilitation Methods

Buildings are damaged due to various factors such as natural disasters, human factors, building design and misuse. Various studies are carried out to ensure the sustainability of the buildings and to strengthen/rehabilitate the buildings with repairable damage. It is necessary to strengthen the structural system to ensure the bearing of the building and to continue the use of the building. On the other hand, considering the effects of buildings on global energy consumption and carbon emissions, seismic reinforcement alone is not sufficient. Therefore, the use of energy-efficient methods gains importance in the strengthening/improvement of buildings.

1.3.1. Energy-Efficient Rehabilitation Methods

For an energy efficient building organization, the building envelope should be shaped to adapt to changing environmental conditions. The most widely used renewable energy sources for heating, cooling, ventilation, lighting, and electricity generation in buildings are solar, wind and geothermal energy. There are two types of systems related to the use of these energy sources in buildings: passive and active systems (Table 7). Systems designed during the design phase of buildings for the use of solar and wind energy for heating, cooling, ventilation, and lighting are considered “passive systems”. Technological products added to the building design can be defined as “active systems” (Türkiye National Agency, 2021).

Table 7. Energy efficient building design principles (Uslusoy Şenyurt & Altın, 2014)

Active Systems	Passive Systems
Shading element (as it is added to the building, it can be simply integrated into the structure. Besides electricity generation, it performs a double function as it provides protection from the sun)	Building form, site selection, orientation, physical properties of the building envelope
Rainscreen (it is mounted on the traditional building element from the outer surface)	The shaping of the building envelope based on the prevailing wind data, the determination of the window openings for this purpose, air filters
Curtain wall systems (Photovoltaic -PV- panel application instead of opaque or transparent glass panel in light curtain wall systems)	Solar control systems and natural ventilation design, atrium design
Double-skin façade systems	Physical properties of the glass material used on the façade (thickness, gap, number of layers, special glasses like low-e)
Building mounted PV systems	Thermal insulation materials and transparent insulation applications
Building integrated PV systems	Trombe wall, green roof applications
Building-integrated wind turbines	Use of ETFE panels, wind chimney and atrium

Passive design can offer both environmental and economic advantages in providing the comfort conditions required for the interior. Passive systems are design approaches that provide the lighting and heating needs required for the interior from solar energy and realize the natural ventilation and cooling function with the design principles based on the use of wind energy (Dikmen, 2011). Passive design principles greatly affect the measures and material decisions to be taken in the building envelope, depending on the climate in which the building is located during the design phase. In the winter period when the heating load is important, the thermal behavior of the building envelope affects the indoor comfort conditions and heating energy. It is necessary to reduce the losses caused by heat conduction in the shell during the heating period. In order to reduce heat losses in the building envelope, thermal insulation is applied. In addition, the use of materials with heat storage capability prevents heat escapes and solar heat is used passively (Uslusoy Şenyurt & Altın, 2014).

The development of the concept of energy efficient building, the increase in sanctions on this issue and the use of renewable energy resources in the building envelope bring different systems together in the light of conscious structuring. Another method for the use of renewable energy sources, which is an input of the energy efficient design parameter, is to consider the building envelope as active system elements. The aim here is to provide the necessary comfort conditions in the interior, that is, to prevent the supply of heating, cooling, and lighting energy, which are the main needs, from exhaustible and expensive sources and to adapt renewable energy sources to the buildings. Active systems developed for this purpose can be defined as a set of mechanical and electronic systems that make solar and wind energy usable indoors. PV panels are used in the building envelope to benefit from solar energy. Wind energy is utilized as active systems through wind turbines (Table 7) (Uslusoy Şenyurt & Altın, 2014).

1.3.2. Seismic Rehabilitation Methods

It is seen in the literature that seismic rehabilitation in traditional reinforced concrete buildings is gathered under two separate headings at the building element and structural system levels.

Strengthening reinforced concrete elements is generally aimed at increasing capacity and/or creating a wrapping effect. Some techniques used can increase the stiffness of the element such as the mantle. For this reason, it is sometimes aimed to increase the rigidity of such applications. It is understood that reinforced concrete or steel jacket, reinforced concrete layer addition, and steel or fibrous plate bonding (for example CFRP) methods are frequently used methods to increase the capacity of the element (Ersoy, 2007). The element-based strengthening approach is the modification of missing elements to increase ductility. The aim here is that the missing elements reach their boundary states in a ductile manner when exposed to tectonic events (Pineda-Porras & Ordaz, 2012).

System improvement, on the other hand, can be defined as creating a new system consisting of rigid vertical elements instead of a weak or inadequate horizontal load bearing system, which is predominantly made up of frames. System improvement emerges as the most reliable, economical, and practical solution when a large number of elements need to be repaired/reinforced and/or the lateral rigidity of the building is insufficient. System improvement is also preferred in cases where the existing building contains some weaknesses such as a soft floor or short column (Ersoy, 2007). For an already-used building, it is important that the new elements to be added to the building are few and that it is designed to significantly increase the load bearing capacity and rigidity of the building (Pineda-Porras & Ordaz, 2012).

1.4. The Aim of The Study

In the national and international literature, there are studies in which energy efficient retrofitting and earthquake resistant (structural) retrofitting are treated separately with different approaches. However, there is a paucity of studies that examine the two approaches together. In this respect, such a holistic approach is considered to be a method that will contribute to a more sustainable and circular economy. It is essential to address these two issues simultaneously with a holistic approach in the field of architecture, especially in a country like Türkiye, which regularly faces the aftermath of earthquakes and is dependent on foreign energy sources. In addition, it has been observed that there are few studies in the literature on the steps to be taken when applying energy efficient and earthquake-resistant improvement methods. This study investigates the steps that can be taken for energy efficiency and seismic retrofitting of the existing residential building stock in Türkiye and attempts to provide a roadmap of these steps.

2. Materials and Method

2.1. Materials

To better understand the issues and methods discussed in the phase of energy efficient and earthquake resistant rehabilitation of residential buildings, firstly energy, circularity and earthquake related issues in Türkiye are included in this study using the national and international literature. Then 7 research that deal with energy efficient and earthquake resistant rehabilitation methods combined and have outputs such as models, applications or simulations in this field were focused on and examined from various perspectives.

In the study, literature review was made on the basis of structural strengthening and energy efficient use in existing reinforced concrete residential buildings and seven research were selected to be examined in these contexts. The titles, authors, years and countries of the selected research, and type (research or practice) are summarized in Table 8.

Table 8. Properties of the research examined within the scope of this article

Title	Authors	Year	Country	Type
Building's eco-efficiency improvements based on reinforced concrete multilayer structural panels	Perez-Garcia, A., Víllora, A. G. and Pérez, G. G.	2014	Spain	Research
Does seismic risk affect the environmental impact of existing buildings?	Belleri A. and Marini A.	2016	Italy	Research
Diagrid solutions for a sustainable seismic, energy, and architectural upgrade of European RC buildings	Labò S., Passoni C., Marini A., Belleri A., Camata G., Riva P. and Spacone E.	2016	Italy	Research
Seismic Strengthening and Energy Efficiency: Towards an Integrated Approach for the Rehabilitation of Existing RC Buildings	Manfredi, V. and Masi, A.	2018	Italy	Research
Combined seismic and energy upgrading of existing reinforced concrete buildings using TRM jacketing and thermal insulation	Gkournelos, P. D., Bournas, D. A., and Triantafillou, T. C.	2019	Italy	Research
Combined retrofit solutions for seismic resilience and energy efficiency of reinforced concrete residential buildings with infill walls	Di Vece, D. and Pampanin, S.	2019	Italy	Research
A probabilistic-based framework for the integrated assessment of seismic and energy economic losses of buildings	Bianchi, S., Ciurlanti, J., Overend, M. and Pampanin, S.	2022	Italy	Research

2.2. Method

In the selection of the research, care was taken to ensure that the buildings subject to rehabilitation are in a residential function and that the rehabilitation applications are in countries with similar climatic and geographical conditions as in Türkiye. During the investigations, the reasons for the rehabilitation of the buildings, the place of the applications in the building, the methods used in the mentioned stages and the integrated rehabilitation methods preferred as a result of the research were examined. Selections consisting of research that offer rehabilitation proposals carried out in Italy and Spain are evaluated in chronological order. The main parameters to be used in the examination of these studies are based on structural reinforcement, energy efficiency, product and energy circularity, accessibility of environmental impact and cost analyses. In line with the data obtained from such investigations, suggestions have been developed regarding the steps to be followed during an energy efficient and earthquake resistant rehabilitations in existing residential buildings. Finally, the study was concluded with a discussion of the obtained findings.

3. Results and Discussion

Perez-Garcia et. al. (2014), conducted seismic and energy retrofit studies by considering reinforced concrete terraced houses located in Gavarda town in the Valencian Community of Spain, built in 2011. In addition to the two-story terraced houses examined, detached and semi-detached houses were also included in the analysis based on the housing typology in the region. Housing typologies were modeled using Architrave 2013 software. By examining the life cycle evaluations of the houses built between 1997 and 2012, the average life of the modeled buildings was taken as 50 years. Structural performance, environmental impact and cost evaluations were made with the application of RCF (Reinforced Concrete Frames), SF (Steel Frames) and MSP (Multi-Layer Structural Panels) to three building typologies (Figure 2). The aforementioned applications were carried out on the brick-filled exterior walls of each building. Various data were obtained by applying the environmental impact (CO_2 emissions, embodied energy and energy consumed over the lifespan) on the buildings, the resistance of the building to snow and earthquake loads and the economic evaluations on the three models produced. The construction and use stages are included and the demolition stage is excluded from the scope of the research. The simulations showed that although the use of RCF and SF in three building types increases the stiffness and bearing capacity of the system, the increase in stiffness reduces the vibration period and increases the effect of earthquake forces. It has been determined that the use of Multilayer Structural Panel (MSP) creates a very rigid and light model with high performance against seismic load. In addition, the inertia mass of the MSP gives small values compared to other models. This is interpreted not only as a stronger structural system but also as an indication of exposure to smaller seismic forces. BEDEC database developed by the Institute of Construction Technology of Catalonia was used in the analysis of CO_2 emissions, embedded energy, and economic cost. It has been determined that the embodied energy contained in the buildings is 60% less in MSP panels compared to the others, and the CO_2 emission is similarly low. It has been determined that the energy lost by the buildings during the average 50-year lifespan is 20% more efficient with MSP and it was found that the use of MSP costs 60-65% less in the economic evaluation. In the research, the use of Multilayer Structural Panels in load-bearing walls, partition walls, foundations and roofs were found to be advantageous compared to other systems (Pérez-García et al., 2014).

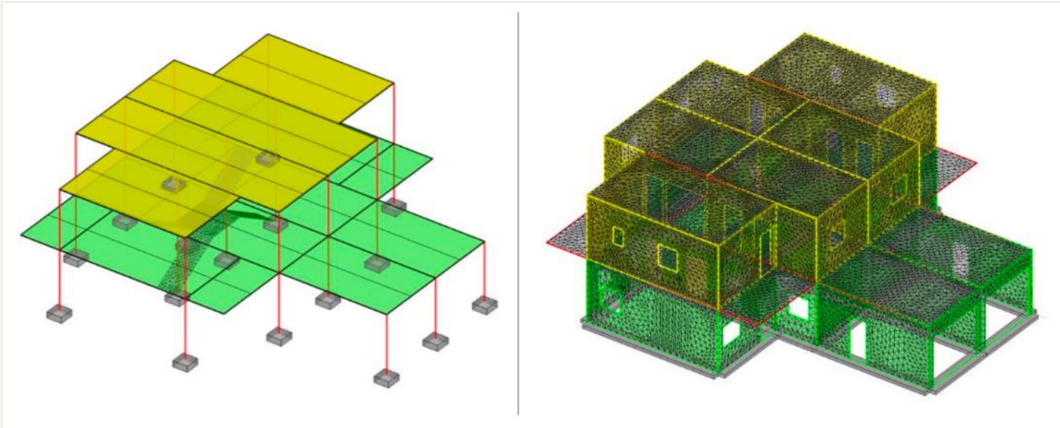

Figure 2. Reinforced Concrete Frame (RCF) and Steel Frame (SF) on the Left, Multi-Layer Structural Panel (MSP) application on the right (Pérez-García et al., 2014)

Belleri & Marini (2016) evaluated different solutions in which energy efficient, seismic retrofitting is considered for two three-story buildings located in regions with moderate to high earthquake risk in Italy and which are not thought to be designed according to current building codes. Three different approaches, namely demolition and reconstruction, energy efficient rehabilitation, seismic and energy efficient rehabilitation, which are thought to be applicable to existing buildings, are discussed in terms of the carbon footprint. The demolition and reconstruction approach were found to be useless as it caused excess building waste and the relocation of individuals living in the building. In the energy efficient remediation method, since the building is not strengthened seismically in case of an earthquake, it is assumed that the building is insufficient due to the possibility of collapse. In energy efficient and seismic retrofitting, it is thought that the life of the building can be preserved for another 50 years without being damaged (Figure 3). Hazard analysis, structural analysis, damage analysis, cost analysis and environmental analysis were performed in the phases of energy efficient and seismic strengthening of the building. Strengthening of the reinforced concrete elements (wrapping with reinforcing steel, epoxy filling, repair of cracks), grout injection to the wall, replacement of damaged wall panels, leakage control of windows and replacement of damaged elements were analyzed. Within the scope of energy efficient rehabilitation, it was preferred to wrap the building with insulation panels. It was observed that there was a decrease in the carbon footprint as a result of energy efficient and seismic rehabilitation and it was concluded that energy efficiency was achieved (Belleri & Marini, 2016).

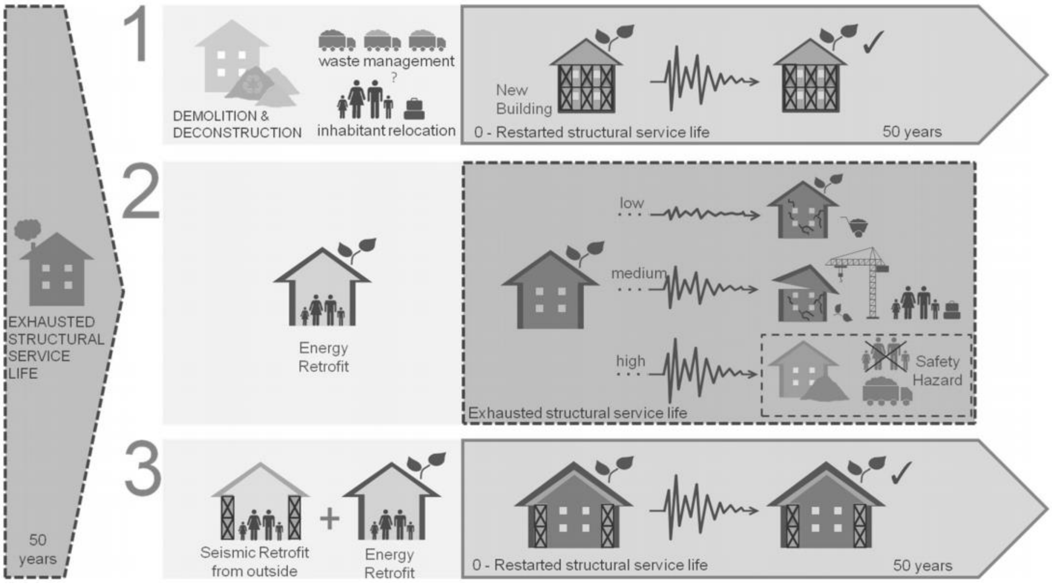

Figure 3. Scenarios of different retrofit methods to be applied to existing buildings (Belleri & Marini, 2016)

Labo et al. (2016) proposed an integrated retrofit approach with the concept of seismic, energy and architectural renewal. The analyzes of these approaches were carried out on an Italian four-story reinforced concrete building built in European architectural features after the Second World War. As a reinforcement model, a fixed diagrid or sliding diagrids that can adapt to different movements can be used. Fixed diagrids can be resolved in two different ways, acting as walls and shells. When resolved as a wall, additional walls/curtains are added depending on the structure. In the shell function, the shell added to the structure can respond to all of the structural, energy and architectural functions. In fixed diagrids, the system reacts more fragilely to earthquakes, while sliding diagrids are systems that allow sliding in the structure due to earthquake movement, and due to these features, the earthquake effect can be damped in the use of this type of system (Figure 4). As a result of the research, it is recommended to use sliding diagrids especially in buildings located in areas with high earthquake risk. Diagrid systems were generally found to be positive due to their ease of assembly, disassembly and repair, and the ability to reuse and recycle structural components (Labo et al., 2016).

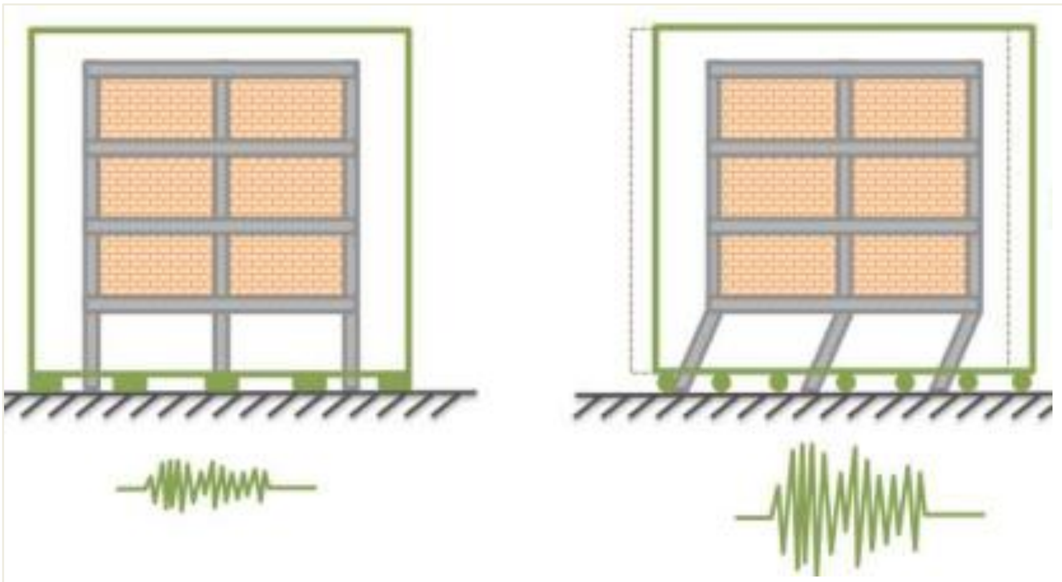

Figure 4. Working principle of sliding diagrids, which are found to be useful against earthquakes in buildings (Labo et al., 2016)

Manfredi & Masi (2018), stated in their research that most of the residential buildings in Italy were built before 1981 when the seismic classification was made and 1991 when the thermal performance criteria were determined. In this context, the ineffectiveness of the existing housing stock in Italy in terms of seismic and thermal insulation performances forms the basis of the research. In the research, the effects of the reinforcement methods applied to increase the thermal and energy performance of the infill walls on the seismic resistance were evaluated. Within the scope of the research, analyzes were made on a six-story residence built after 1971, which represents the existing buildings and models were produced. The existing building model (C1), the model in which the outer layer of the infill walls is replaced with a panel with good thermal insulation properties (C2), and the double-skin façade model (C3) which is created by adding the new reinforced concrete frames seen in Figure 5, are examined in terms of seismic and energy. Afterwards, the C2 and C3 models were compared with the existing building - C1. An Incremental Dynamic Analysis (IDA) was conducted to evaluate the seismic performance. In the energy efficiency assessment, the Italian and European Energy Efficiency Provisions in force are discussed. As a result of the research, the seismic performance and energy efficiency of the C2 model were found to be positive and it was determined that these models could be applied in buildings with seismic risk. It has been stated that the application of the C3 model, especially in high-risk reinforced concrete houses in terms of seismic performance, will reduce life safety and energy losses (Figure 6).

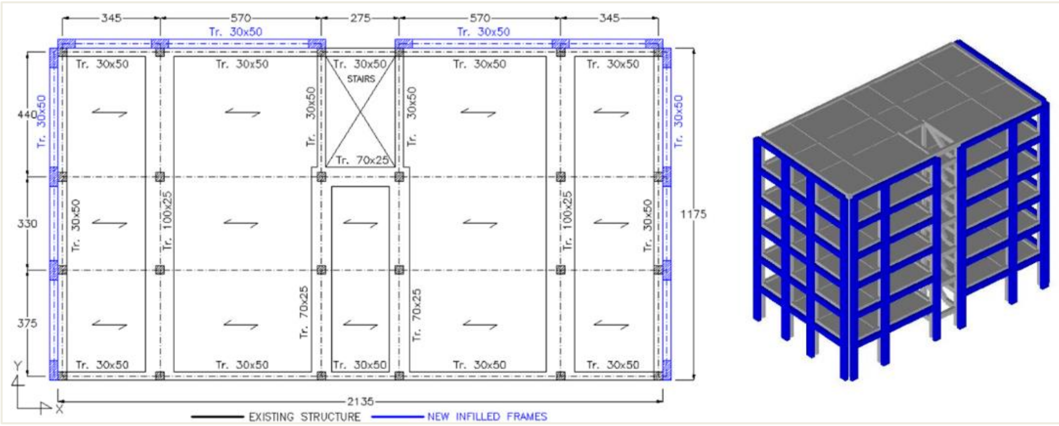

Figure 5. The plan and 3D view of the building reinforced with the C3 model (Manfredi & Masi, 2018)

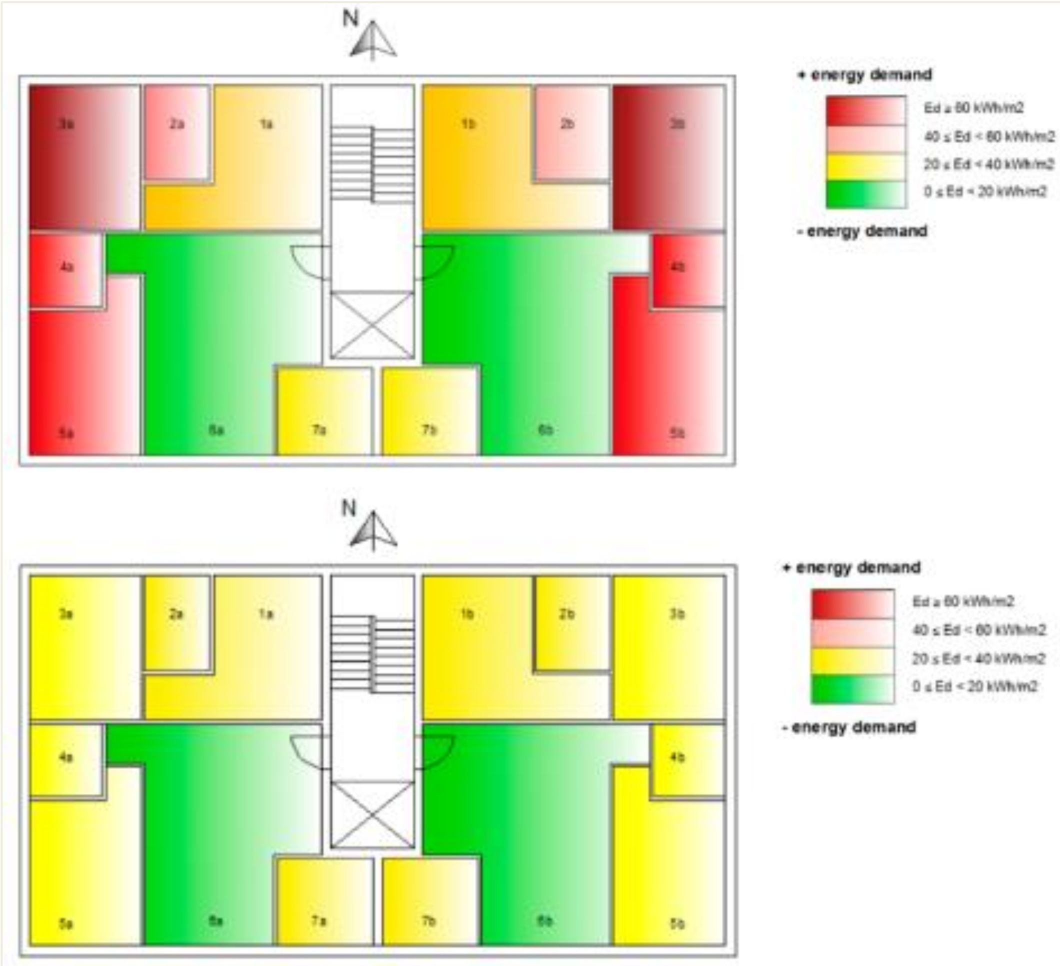

Figure 6. Comparison of the required energy as a result of the C1 (top) and C2 (bottom) model (Manfredi & Masi, 2018)

Gkournelos et al. (2019), carried out studies with the approach of strengthening the seismic and energy efficiency of reinforced concrete buildings built in Italy in the years 1960-1980. Building models of 2, 5 and 5 floors (raised by pilots) were produced by reference to the existing reinforced concrete buildings in Bergamo, Florence, Rome, and Catania. The research, which starts with the examination of the problems in reinforced concrete buildings, deals with the proposed structural strengthening methods and integration with energy improvement to overcome these problems. Within the scope of the research, reinforcement with FRP (Fiber Reinforced Polymer) and TRM (Textile Reinforced Mortar) were evaluated and especially TRM performance was examined. TRM has been applied to the load-bearing system and exterior walls in three building typologies as two-sided (inside-outside) or one-sided. This strengthening method, which is applied differently in buildings or floors, is expected to provide both seismic reinforcement and energy efficiency. Earthquake and energy simulations were produced separately and then dealt with holistically. Earthquake simulations were performed with OpenSees and energy simulations with EnergyPlus software. In seismic modeling, a total of 11 earthquake records were taken from Greece, Italy and Türkiye, and dynamic analysis was performed. In the energy simulation, material thickness, thermal behavior, density, and specific heat were taken as basis, and thermal insulation was prioritized. As a result of the research, structural reinforcement has been achieved in all building types using TRM and energy efficiency has increased. As a result, this application which reduces economic losses by 25%, is recommended in terms of seismic, energy and economic recovery (Gkournelos et al., 2019).

Di Vece & Pampanin (2019) evaluated combined energy efficient and seismic retrofit alternatives for a three-storey building built in the 1970s in L'Aquila, Italy. The building examined in the research does not meet today's earthquake code values, and in terms of climatic conditions, it has 451% more energy consumption than the minimum acceptable values in the current regulation in terms of criteria such as building envelope, insulation layers, windows, and cooling system. Structural strengthening methods examined in the research are G-FRP (Glass-Fiber Reinforced Polymer), Haunches Retrofit Solution (HRS) and PRESS systems (Figure 7). In solutions for energy efficiency, gap insulation with polyurethane foam (by filling the 60 mm gap) on non-load-bearing walls, external insulation glued on expanded polystyrene panel (80 mm) and wood cladding panel alternatives with cork panels were evaluated. As a result of the research, the use of the PRESS system for structural improvement and the replacement of the coating on the non-bearing walls for energy efficiency were revealed as the most appropriate solution. Cost estimation is excluded (Di Vece & Pampanin, 2019).

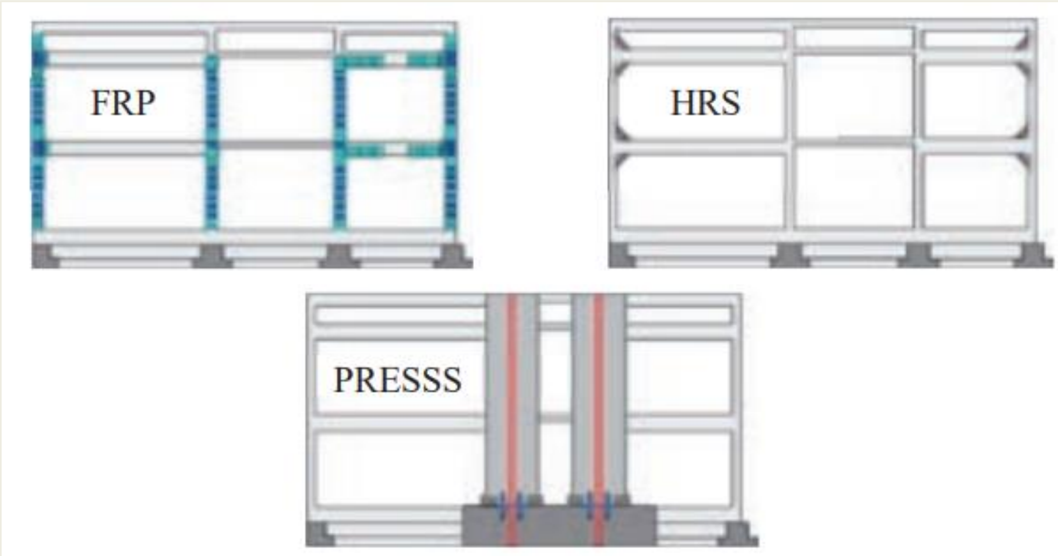

Figure 7. FRP, HRS and PRESS structural improvement methods examined in the research (Di Vece & Pampanin, 2019)

Bianchi et al. (2022), developed a probability-based proposal to measure the performance of integrated energy efficient and seismic retrofitting methods of a five-story reinforced concrete (first three floors used as offices, 3rd and 4th floors used as residences) for the conditions in the Italian city of Messina, which has a high earthquake risk and temperate Mediterranean climate, and Bolzano, which has a low earthquake risk and continental climate. In this context, different structural reinforcement and energy efficient strategies were examined over a model building with EnergyPlus and Python programs. The structural strengthening methods examined in the research are on strengthening the column-beam junctions of the model building (cast-in-situ concrete or low-damage PRESS system), two different elements used in the assembly of the façade elements, and the use of two different glass thicknesses on the façade. In addition, different solutions for ceilings and partition walls were examined. Solutions for energy efficiency are alternatives produced by different stratification on walls (concrete panel/sandwich panel), changing the type of glass used (double glazing and low-e coated double glazing), differentiation of u-value, sun screen and air filter installation (Figure 8). As a result of the research, it has been revealed that the case of energy efficiency solutions using PRESS system, sandwich panel, low-e coated double glazing, sun screen and air filter will be the most suitable solution for the building with 95% probability. In the research, cost analyzes for the alternatives were made for different earthquake intensities and for two locations. According to this, the use of PRESS system, low-e glass, sun screen and air filter, which is seen to be the most suitable method, is also lower in cost compared to others. All of the applied methods are positive in that there is no need for building demolition and that the existing building can be used (Bianchi et al., 2022).

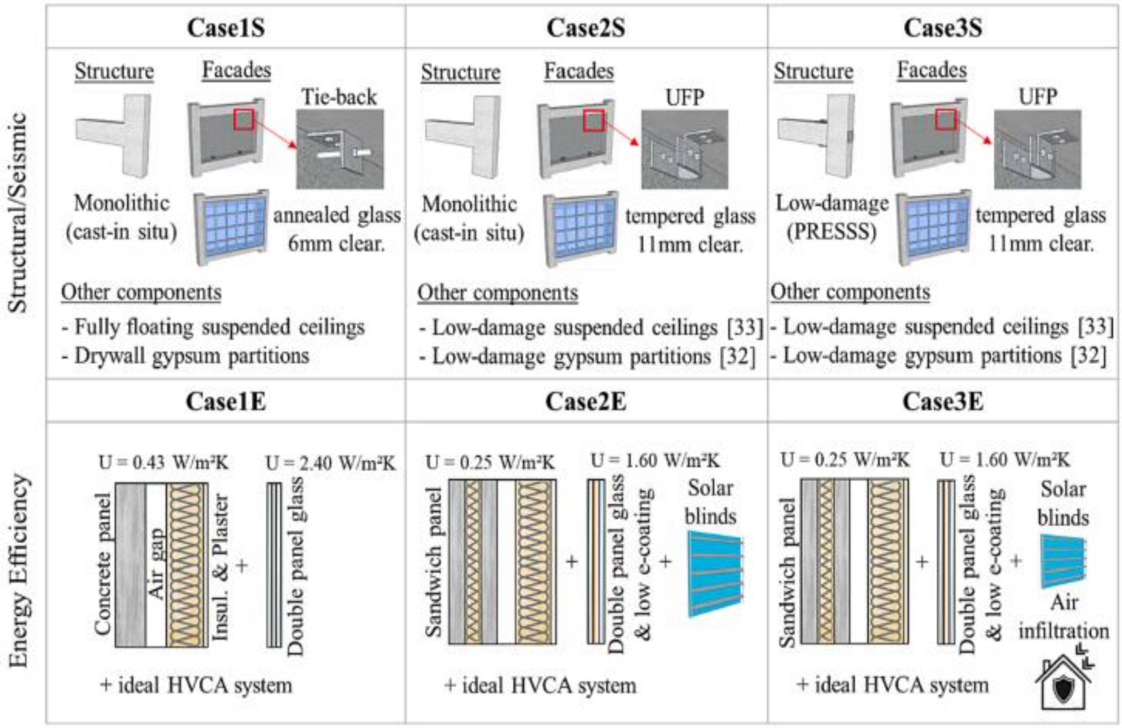

Figure 8. Structural and energy efficient improvement methods examined in the research (Bianchi et al., 2022)

In studies that integrate earthquake and energy efficient improvement approach, the reason for improvement-reinforcement is to ensure that the buildings become resistant to earthquake hazards and to increase energy efficiency. Studies on existing reinforced residential buildings in Italy and Spain were examined in chronological order. Improvements applied to existing houses or models produced from existing houses have been evaluated with different approaches and software. The load-bearing system, structural elements and applications on the façade are discussed in the context of structural and energy efficient rehabilitation. In the studies examined, the preferred improvement methods were determined as an additional exoskeleton to the load-bearing system, the use of mortar on the infill walls, new facade cladding, improvement of the insulation layers, the use of reinforcement steel, low-e glass, sun screen and air filter. The environmental impacts and accessible cost analyze that will occur as a result of the implementation of the applications have been evaluated. The CO_2 emission, embodied energy, energy consumed during the usage phase and waste generation conditions of the building are stated to the extent that they can be reached during the design, construction, use and demolition phases. In the studies dealing with cost analysis, profits were made or separate cost calculations were prepared. The studies examined present positive results with the mentioned inputs in seismic and energy retrofitting (Table 9).

Table 9. Improvement and strengthening methods used in the studies examined

Reference	Rehabilitation Location	Structural Rehabilitation Method	Energy-Efficient Rehabilitation Method	Preferred Rehabilitation Method	Rehabilitation Cost Impact
Perez-Garcia et. al (2014)	Structural system + building elements + facade	Element reinforcement	Insulation on exterior walls	Multi-layer structural panel	%60-65 cheaper
Belleri & Marini (2016)	Structural system + building elements + facade	Adding structural system + element repair	Insulation	Reinforcing steels + epoxy filler + insulation layer	unspecified
Labo et. al (2016)	Structural system + facade	Adding a shell frame	Façade design	Exoskeleton + solar control	unspecified
Manfredi & Masi (2018)	Structural system + building elements + facade	Adding a shell frame	Façade design	Exoskeleton + new cladding	unspecified
Gkournelos et. al (2019)	Structural system + facade	Structural system reinforcement	Insulation on exterior walls	Textile reinforced mortar (TRM)	%25 cheaper
Di Vece & Pampanin (2019)	Structural system + facade	Structural system reinforcement	Façade design	PRESS + new cladding	unspecified
Bianchi et. al (2022)	Structural system + facade	Structural system reinforcement	Arrangement of transparent façade elements	PRESS + low-e glass + sun screen + air filter	cheaper

Considering the studies examined, it can be said that similar solutions can be preferred for earthquake resistant and energy efficient rehabilitation of buildings in Türkiye as well. However, some steps need to be followed during the adaptation of the mentioned solutions to the buildings. First of all, it is necessary to determine the weak points of the buildings in case of structural damage caused by earthquakes. Afterwards, reinforcement studies should be carried out for the determined points. It is observed that different stages are followed in the process of energy efficient and seismic rehabilitation of residential buildings. In order to be an exemplary method for future research, the mentioned stages can be listed as follows in the light of the data obtained from the research examined within the scope of the study (Gülmez, 2010; Koç, 2023; Naş, 2019; Yerci, 2001; Yiğit, 2002):

i. <u>Data collection on the building:</u> Whether the building is applied in accordance with the projects or not can be determined through the obtained architectural, static, mechanical, and electrical projects. It is important to obtain the projects of the existing building before starting the determination works.

ii. <u>Survey drawings of the existing building:</u> The load-bearing elements in the current state of the building should be compared with the project, and the missing or damaged items should be marked on the project. In this way, the elements that will be handled in the future retrofitting project will be determined. If the project could not be reached, the survey of the entire building should be taken and the necessary studies should be done on these drawings.

iii. <u>Determination of damage:</u> At the stage of deciding whether to strengthen the building or not, damage assessment should be done as a priority. When it is determined that the building is heavily damaged, a demolition decision can be made for the building. However, in case of less damage, it may be preferable to strengthen the building. In times of earthquake risk, it may not be possible to obtain the projects of the buildings and to take the survey. In this case, the damage assessment stage can be encountered as the first stage. Damage assessment studies may need to be continued throughout the retrofit/remediation process due to aftershocks that are likely to occur during detection.

iv. <u>Determination of building concrete quality:</u> Concrete strength can be measured by taking concrete samples through cores. In order to measure the strength in a consistent manner, samples must be taken from the load-bearing elements located on different floors.

v. Determination of the number, order and quality of the reinforcements: The dimensions of the horizontal and vertical reinforcements and their quantities should be checked by removing the pass margin in the load-bearing elements.

vi. Ground survey report: The characteristics of the ground on which the building is built can be obtained by drilling. Earthquake behavior on the ground, ground water level, soil safety stress can be measured in this way.

vii. Seismic reinforcement project: As a result of the calculations made depending on the damage size of the building, the strengthening methods are determined. Element-based methods are used in the strengthening phase of the building. According to the static data obtained, system-based reinforcement can also be preferred.

viii. Including energy efficient methods: Today, only seismic strengthening of buildings is not sufficient in terms of environmental effects and architectural aesthetics of buildings. In order to ensure the load bearing of the buildings, after the necessary static calculations are made, the selection of the strengthening method, which is thought to be carried out, should be planned considering the energy efficiency, environmental impact, and architectural concerns of the building.

ix. Cost analysis: While performing cost analysis during the strengthening and improvement stages of buildings, primarily structural losses are considered. Architectural and load-bearing elements, mechanical and electrical equipment, elevators, and other elements in the building content constitute structural losses. Human losses and injuries that require medical attention in damage to buildings due to earthquakes are also included in the cost analysis. In addition to these, in case of evacuation of buildings, emergency accommodation costs arise in the process of creating spaces where individuals can settle. Repair time of damaged buildings, rental cost of places and moving cost affect the total cost (FEMA, 1999; Yanmaz & Luş, 2005). In addition to all these costs, the cost of reinforcement differs according to the preferred reinforcement method as a result of the decision to repair and strengthen the building. As a result of the data obtained from the studies examined, it is seen that the cost differs according to the location of the country where the study is carried out, the characteristics of the building, the extent of damage to the structure and individuals, the reason for the reinforcement, and the preferred reinforcement or improvement method. Therefore, it is not possible to make a definite judgment about which method is more costly.

x. Environmental impact analysis: It is necessary to measure the effects of the planned strengthening and improvement methods on the environment. It is possible for the building to reach a healthy state by providing solutions not only to provide energy efficiency to the building, but also to reduce the negative impact of the building on its environment. The effects of the relevant solutions can be measured with analysis, model and simulation programs as seen in the studies discussed.

The rehabilitation stages that deal with seismic resistance and energy efficiency in buildings in an integrated way can be summarized as in Figure 9. It is thought that the most suitable energy efficient seismic rehabilitation method for a residential building can be determined through the data obtained by following the aforementioned steps. These methods are related to many professional working fields. Therefore, in this process, the necessity of cooperation between different disciplines gains importance.

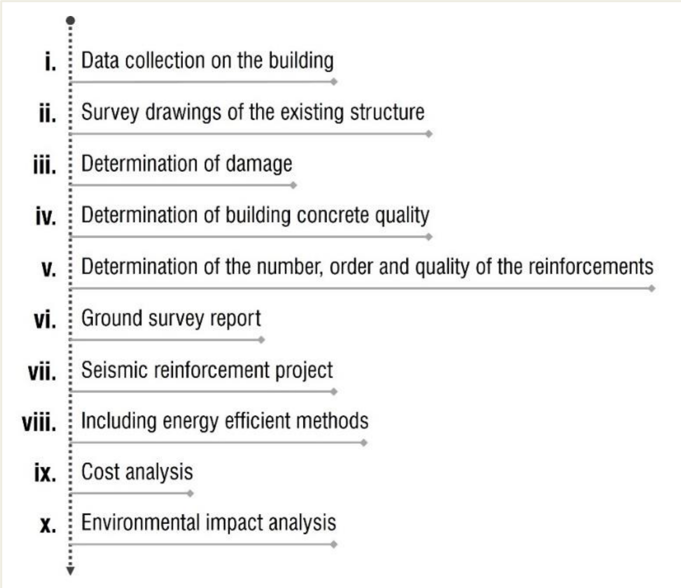

Figure 9. Energy efficient and seismic rehabilitation application steps

4. Conclusion and Recommendations

In the study, a literature review was conducted by considering earthquake-resistant (structural) strengthening and energy efficient rehabilitation approaches. Seven research on an international scale that provide practices and suggestions for the rehabilitation of existing reinforced concrete residential buildings were examined. In studies on reinforced concrete residential buildings in Italy and Spain, analyzes were carried out through simulation programs on existing buildings and produced models. In the research, suggestions were presented for the structural strengthening of reinforced concrete buildings, mainly against existing earthquake risks. The effects of these reinforcement methods on energy efficiency were examined and supported by additional methods based on the efficient use of energy. Research has demonstrated that assessing the effects of energy-efficient retrofitting, alongside seismic strengthening procedures, is crucial for evaluating the impact on the environment, building longevity, and occupant well-being. Since the recommended strengthening methods were discussed in the seven research examined, the following results were obtained:

- In terms of rehabilitation/strengthening areas, the load-bearing system was generally applied to building elements and facades.
- In terms of structural strengthening methods, structure strengthening, shell frame addition and element strengthening methods were preferred.
- Building envelope designs and insulation applied in the building have come to the fore in energy efficient rehabilitation methods.
- Exoskeleton, PRESS system, insulation layer, solar control and low-e glass usage were preferred as rehabilitation methods.
- It was observed that cost analysis was performed in three of the research, two of which were quantitative, one of which was qualitative, and four of which were not.

With this study, in which research conducted in regions with high earthquake risk was selectively examined, the steps to be followed in the strengthening and rehabilitation of buildings were determined and a road map was proposed.

In order to use energy efficient methods during the rehabilitation and strengthening of buildings, awareness in this field needs to be increased. In creating this awareness, the training given to professions in the construction sector gains importance. In carrying out rehabilitation works, the number of applications in the sector can be increased through government support. It is envisaged that the study conducted can be a reference for studies to be carried out in the future.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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