Rapid Multi-Risk Needs Evaluation and Planning Platform

101193586 - EMERGE - UCPM-2024-KAPP-PV

CBR Exposure, Resources and Capacity Portfolio

Residential, Commercial and Industrial Buildings Vulnerability Assessment
Prioritization of Interventions

Work package:	03
Deliverable Number:	3.2
Lead Beneficiary:	AUTH
Coordinator:	IZIIS
Contributing Beneficiaries:	EUCENTRE, AUTH, UPT-FCE, IUSS, CMC, PRD, AKMC, NOA, INFRATECH
Dissemination Level:	Public
Version:	1.0
Due Date:	November 30, 2025
Submission Date:	November 30, 2025

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WP-03 | D.3.2

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November 30, 2025

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Executive summary

This deliverable (D3.2) presents a compiled exposure model for residential, commercial and industrial buildings within the EMERGE project. The work is entirely new and involves defining, developing, and enhancing an exposure model for residential, commercial, and industrial buildings across Albania, Greece, and North Macedonia based on available data sources. This effort expands the multi-risk assessment previously focused on basic services and transport infrastructure under the CRISIS project, enabling a more comprehensive evaluation that now also incorporates the building stock. The objective of this activity is to collect, refine and expand the exposure and vulnerability datasets to support evidence-based decision-making for risk reduction and to enhance regional disaster preparedness and emergency management capacities.

The report begins with an overview of the harmonized cross-border seismic and landslide hazard assessment, integrating national, regional, and European perspectives. The methodologies for earthquake and landslide hazard evaluation are summarized, with emphasis on their application to infrastructure systems across the three participating countries (CRISIS project).

Subsequently, the cross-border exposure model is described, covering three building categories:

- Residential buildings
- Commercial buildings
- Industrial buildings

For each country, data has been collected and harmonized according to a consistent methodology, enabling comparative assessment and regional synthesis. The analysis provides insight into the distribution, structural typologies, and age profiles of the exposed assets, with particular attention to their seismic and landslide vulnerability characteristics.

The last section presents the main features of the fragility models adopted for assessing the vulnerability of residential, commercial, and industrial buildings located within the CBR.

1. Introduction

Exposure is a fundamental component of disaster risk assessment, representing the presence of people, assets, and infrastructure that may be affected by hazardous events (UNDRR, 2017). Reliable exposure data are essential for quantifying potential impacts, including property damage, economic losses, and human casualties, and for identifying effective measures to mitigate the risk (GAR, 2019). In this context, exposure modeling provides the spatial foundation for vulnerability and risk analysis by integrating geospatial, structural, and socio-economic information.

This deliverable (D3.2) is part of Work Package 3 (WP3) of the EMERGE project, which aims to enhance regional risk assessment capacity through the modeling of exposure, vulnerability, and capacity. The work is entirely new and involves defining, developing, and enhancing an exposure model for residential, commercial, and industrial buildings across CBR between Albania, Greece, and North Macedonia (Figure 1).

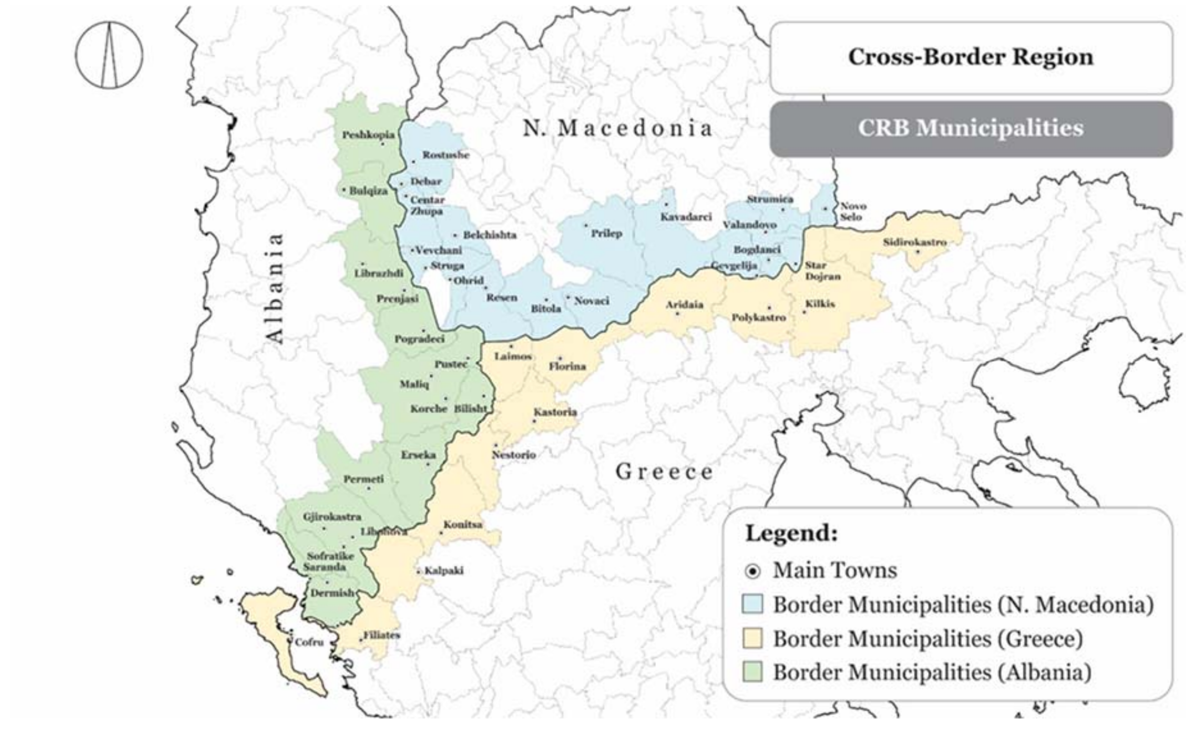


Figure 1. Integrated cross-border region; Main cities

The focus of Task 3.2 is to collect datasets of exposure model consisting of residential, commercial, and industrial buildings across CBR and to support prioritization of interventions based on the exposure portfolio. Furthermore, it contributes to improving data sharing and coordination among National Civil Protection Authorities (NCPAs), enhancing collective capacity for multi-risk assessment and disaster preparedness in the CBR area. It should be emphasized that the exposure model is developed exclusively from available national datasets—such as statistical office records, census data at the municipal level, European Seismic Risk Model - ESRM20 (Crowley et al, 2021), relevant projects, studies, documentation and other publicly available sources of information — and does not involve any field investigations.

This document presents the methodology and results related to the defining of the regional exposure building model, supporting the overall EMERGE objective of strengthening risk reduction and resilience-building across partner regions. In this framework, Section 2 briefly illustrates the main hazards considered in the EMERGE project, i.e. earthquakes and landslides, based on the harmonized multi-hazard approach set up within the CRISIS project for the CBR. Section 3 describes the exposure model consisting of residential, commercial, and industrial buildings across CBR. With reference to the above assets, Section 4 provides the key features of the fragility models adopted for assessing vulnerability to the considered seismic hazards. Finally, concluding remarks are summarized in Section 5.

2. Recap of the main features of the harmonized cross-border seismic and landslide hazard assessment

In this section, the harmonized approach for multi-hazard assessment in the CBR is briefly illustrated (Section 2.1). Then, Section 2.2 and Section 2.3 focus on the main addressed hazards, which are earthquakes and landslides, respectively.

2.1 Brief illustration of the methodology

A comprehensive risk assessment of critical infrastructure requires an integrated, multi-hazard approach combining advanced geospatial analysis, historical data, and modern probabilistic models. Previously concluded CRISIS project emphasized harmonization across the national borders among North Macedonia, Albania, and Greece and the regional context for seismic and landslide hazards, supporting resilient planning for buildings and transport routes (CRISIS D2.2, 2021 and CRISIS D2.3, 2021).

Key principles include:

- Reviewing national datasets, building codes and hazard mapping efforts for each country;
- Utilizing harmonized European and global hazard assessment tools (e.g., ESHM20 (the 2020 European Seismic Hazard Model) (Danciu et al., 2024) for seismicity, ELSUS v2 (Pan-European landslide susceptibility mapping for landslide susceptibility) (Wilde et al., 2018);
- Applying consistent probabilistic and scenario-based modeling to inform mitigation and planning;
- Cross-referencing infrastructure exposure and vulnerability for both natural hazards.

This methodology was framed by the need for zonation maps and susceptibility indices, scenario-based risk assessment and multi-criteria evaluation methods. In regions with complex terrain and incomplete inventories, harmonized large-scale approaches are recommended, supported by detailed local studies as available.

2.2 Earthquake hazard

Earthquake hazard assessment for critical infrastructure in the cross-border region is founded upon a rigorous review of available national, regional, and European models, culminating in the adoption of the state-of-the-art ESHM20 (European Seismic Hazard Model, (Danciu et al., 2024)) to ensure methodological harmonization.

2.1.1 National Perspective

In North Macedonia, seismic hazard assessment has evolved through several national models and seismotectonic zoning efforts since the 1960s, with contributions from the Institute of Earthquake Engineering and Engineering Seismology (IZIIS). These models incorporate historical seismicity, GPS-based tectonic measurements, and probabilistic mapping. Building codes have been updated over time towards Eurocode 8 (CEN, 2004-2006) compatibility - recent national annexes provide seismic zoning in acceleration units for modern design.

Albania's approach, while rooted in 1989's KTP-N2-89 code, has expanded through seismic microzonation of cities and regions. Hazard maps with return periods of 475 years have been produced by the Academy of Science and the Institute of GeoSciences, Energy, Water and Environment (IGEWE). Eurocode-based seismic design is increasingly used, supplemented by historical catalogues and microzonation studies.

Greece implements zonal seismic hazard mapping reflecting extensive studies since the 1970s. Official seismic zoning divides the country into three zones (based on the updated 2003 code) with peak ground acceleration ranges of 0.16g, 0.24g and 0.36g for a 475-year return period. These reflect historic earthquake exposures and are integrated into engineering codes.

2.1.2 Regional and European Perspective

Regional harmonization was enhanced by the BSHAP (Harmonization of Seismic Hazard Maps for the Western Balkan Countries) project (Salic et al., 2017) for the Western Balkans, using smooth-gridded seismicity with results in peak ground acceleration (PGA) for return periods aligned with Eurocode 8.

The SHARE Project – ESHM13 (Seismic Hazard Harmonization in Europe, www.share-eu.org, Giardini et al., 2014) and EMME Project (Earthquake Model of the Middle East, www.emme-gem.org, Erdik et al., 2012) integrate region-wide catalogues and logic-tree frameworks, capturing aleatory and epistemic uncertainties in scenario modeling and ground motion prediction, with outputs accessible for site-specific and regional analysis.

The ESHM20 provides probabilistic hazard assessment for Europe and Turkey, incorporating a range of source models (area, fault/background, kernel-smoothed) and site conditions, spanning 5000 to 73 years return periods.

2.1.3 Application to Infrastructure

Harmonized hazard maps (ESHM20), scenario-based analysis, and uniform hazard spectra are applied to characterize the seismic hazard levels affecting major towns and key transport corridors. PGA values typically range between 0.20–0.45g for the mean 475-year return-period hazard, with maximum values observed in southern Albania and western Greece, and substantial values in the Debar-Librazhd (AL-MK border) and Valandovo-Kilkis (MK-GR border) zones.

2.3 Landslide hazard

The assessment of landslide hazard for cross-border critical infrastructure follows a meticulous review of inventory maps, susceptibility zonation and probabilistic approaches at national, regional, and European level.

2.3.1 National Inventories and Susceptibility Mapping

In North Macedonia, the mountainous terrain (over 79% hills/mountains) results in frequent landslides triggered by rainfall, snowmelt, or seismic activity. Multiple partial inventories exist, but national-level coverage is incomplete. Key research contributions identified GIS-based susceptibility and earthquake-induced landslide risk, emphasizing the critical need for national strategies integrating different triggering events for future hazard management (CRISIS D2.3, 2021, Bojadjieva et al., 2025).

Albania, similarly, mountainous, has compiled a landslide inventory and susceptibility mapping at scales of 1:150,000 (regional) and 1:1,200,000 (national) by the Geological Survey of Albania (GSA). The methodology combines heuristic and bivariate statistical methods, evaluating terrain slope, aspect, lithology, land cover, hydrology, precipitation and seismicity. Over 2900 landslides have been catalogued, with comprehensive forms documenting location, geomorphology, geology and hydrotechnical data (GSA, 2015).

In Greece, landslide susceptibility mapping uses extensive historic inventory data (over 1600 cases pre-2010), multivariate statistical analysis and digital thematic maps of geological, hydrological, climatic, land use and population factors. Zonation is expressed by the Landslide Susceptibility Index (LSI), with six classes from very low to extremely high (Sabatakakis et al., 2013). However, like its neighbors, no complete hazard map exists at the national level.

2.3.2 Regional and European Approach

Cross-border harmonization integrates national findings with large-scale European models. The ELSUS v2 Pan-European Landslide Susceptibility Map (Wilde et al., 2018) is adopted for harmonized assessment, using multi-criteria evaluation of terrain gradient, lithology, and land cover datasets. Statistical and expert-based confidence levels are assigned; up to 65% of the cross-border region is classified as having high or very high landslide susceptibility, reflecting the dominance of mountainous terrain.

Triggering mechanisms are summarized, with emphasis on rainfall, earthquakes, and anthropogenic activities (infrastructure construction, land use change). Susceptibility, while predicting where landslides may occur, does not account for timing or magnitude. Hazards are quantified by combining spatial, temporal and event magnitude probabilities.

3. Cross border exposure model

3.1. Methodology

The partners in CBR have different frameworks/regulations regarding design, construction and maintenance of the targeted building stock in this task. They involve different institutions and employ different ways of gathering information on existing building structures within their networks. Each of them may use different methods and systems for keeping records on their assets. Therefore, there is no readily available inventory which covers the entire stock of residential, commercial and industrial buildings. Regarding the above, the collection of data is done exclusively from available national datasets—such as statistical office records, census data at the municipal level, European Seismic Risk Model - ESRM20 (Crowley et al, 2021), relevant projects, studies, documentation and other publicly available sources of information —and does not involve any field investigations.

A regional exposure database has been created based on contemporary practice and research compatible with the GEM Exposure Database (https://storage.globalquakemodel.org/what/physical-integrated-risk/exposure-database/). This database is specific enough to conduct numerical analysis and develop or select proper vulnerability functions.

The building attributes are divided into 3 categories:

1. General information on the building
2. Structural characteristics of the building
3. Additional information

The first two categories are further subdivided as outlined in Table 1 below.

Table 1. Building attributes

Category	**Attributes**
General information	Id (sequence number)

on the building	**Type of Building** **Municipality** **Latitude* [°]** **Longitude* [°]** **N° of Buildings** Number of dwellings
Structural characteristics of the building	**Number of stories above ground** **Design year/Construction period** Date of last retrofit (if any) Physical condition / maintenance Building cost [€/m2] **Main structural material** Typology and organization of the resistant system (RC) Typology and organization of the resistant system (Masonry) Type and organization of the resistant system (Steel) Type and organization of the (Precast) Type of connection Beam/columns (Precast) Horizontal structure

During online discussion and consultation with EUCENTRE, who is responsible for the development of Rapid Needs Assessment Web-based Platform - EMERGE WBP (main project outcome), the below attributes marked as bold in the above table 1 are selected as essential ones as input data for further analysis.

The sections below illustrate the exposure model in each of the CBR partner countries focusing on residential, commercial and industrial buildings.

3.2. Residential Buildings

3.2.1. Albania

The required attributes of the residential building assets are collected for each municipality at the Albanian side of the CBR and from multiple sources, as indicated below:

- Census 2011 (INSTAT https://www.instat.gov.al/sq/)
- National Disaster Risk Assessment in Albania (DCM No. 168, 24.03.2023)
- Experts' knowledge

The total number of residential buildings is 114,875. Their distribution by municipality is presented in Figure 2. Of these, 100,304 are masonry structures and 14,571 are reinforced concrete buildings, classified into three categories according to design year/ construction period reflecting the evolution of seismic code requirements (Figure 3). The distribution of buildings construction area by municipality is given in Figure 4, and the classification according to design year and material is given in Figure 5.

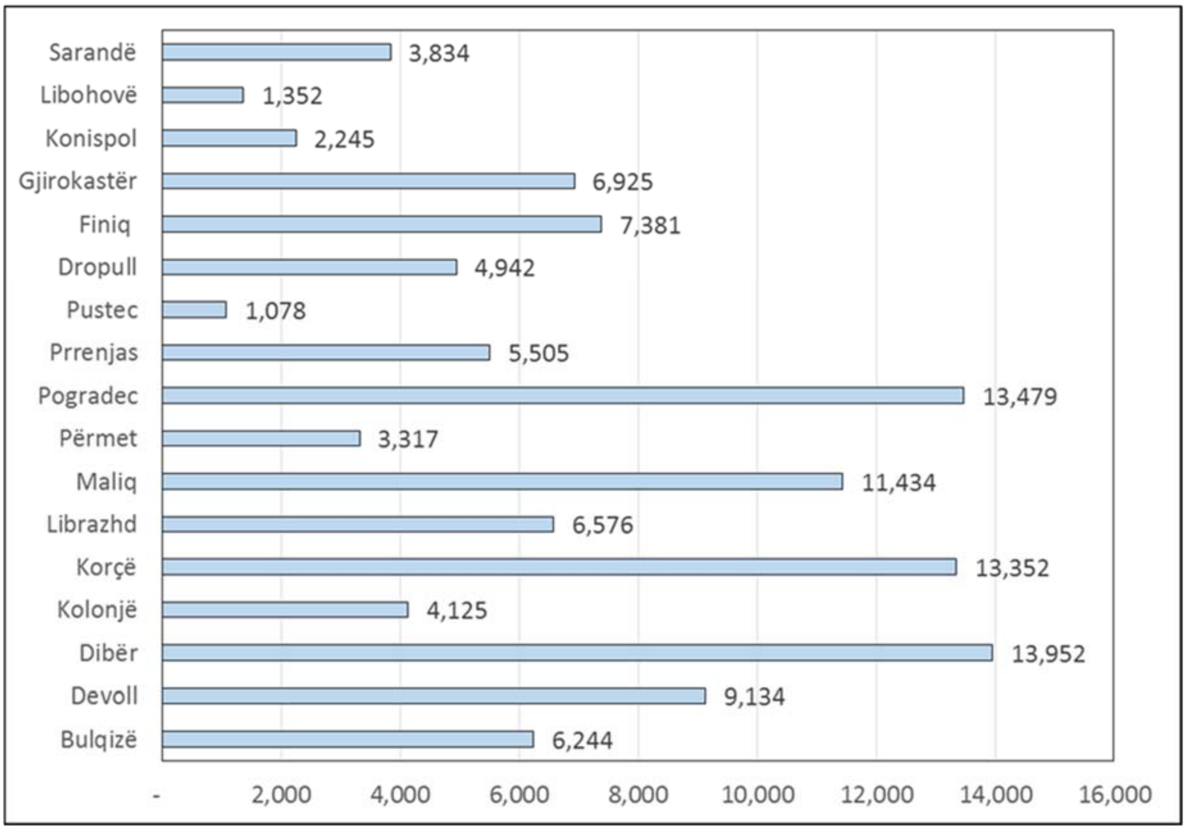


Figure 2. Distribution of residential buildings per municipality

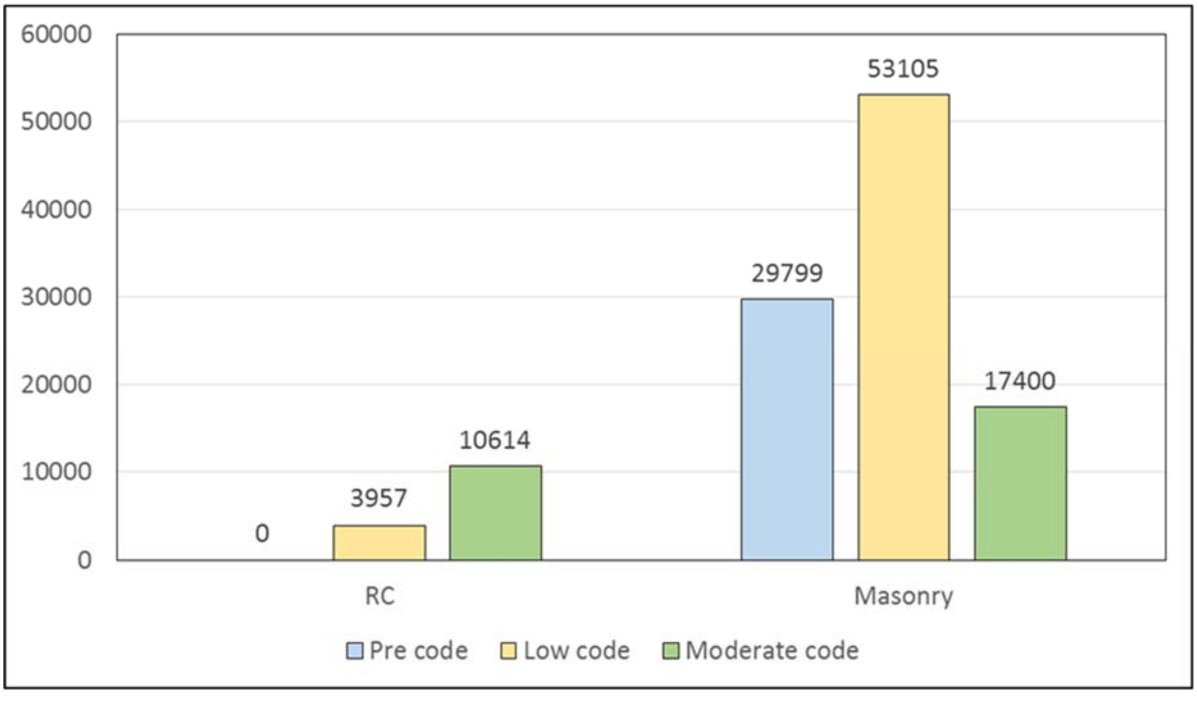


Figure 3. Distribution of residential buildings by structural material and code

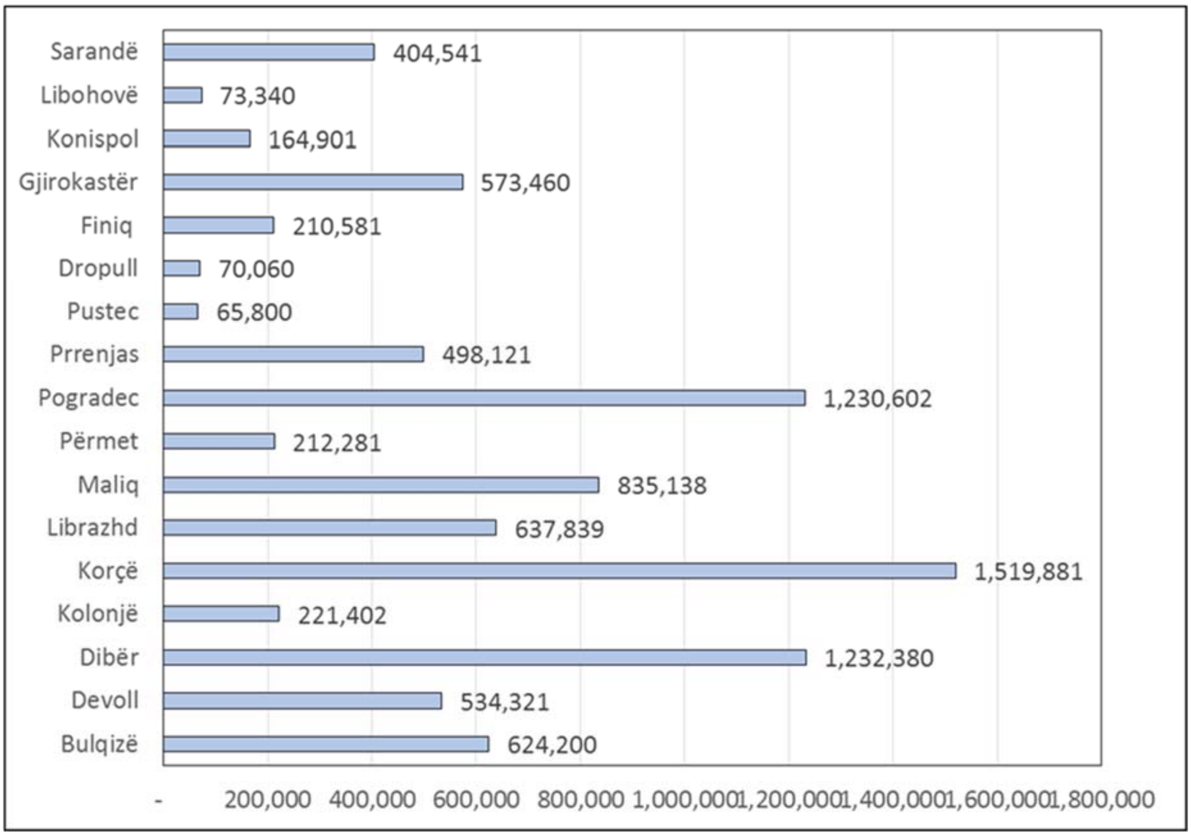


Figure 4. Distribution of residential buildings construction area per municipality

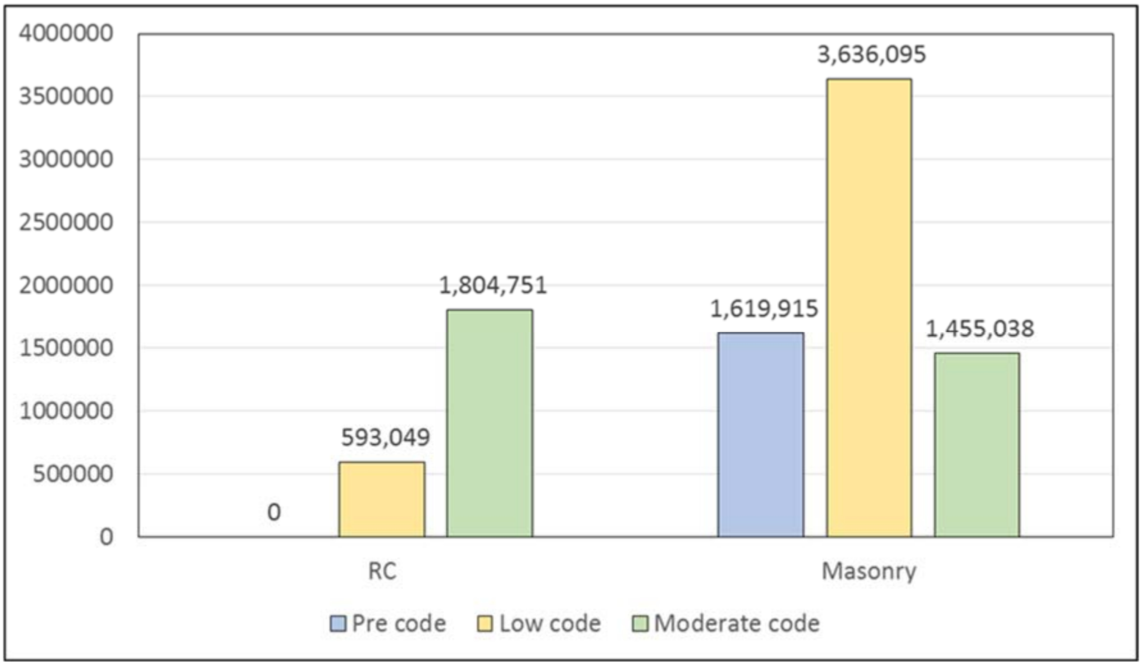


Figure 5. Distribution of residential buildings construction area by structural material and code

3.2.2 Greece

The herein developed exposure model for the residential buildings of the Greek part of the CBR is based on the results of the national buildings census of 2011 (ELSTAT 2011). The census includes information on the type of use, main construction material, period of construction, number of stories, type of roof, existence of pilotis (soft story) and number of residencies. The developed exposure model is aggregated at settlement level and includes a total of 135,755 buildings with exclusive or primary residential use. These buildings are distributed to the different municipalities of the Greek part of the CBR according to **Error! Reference source not found.**.

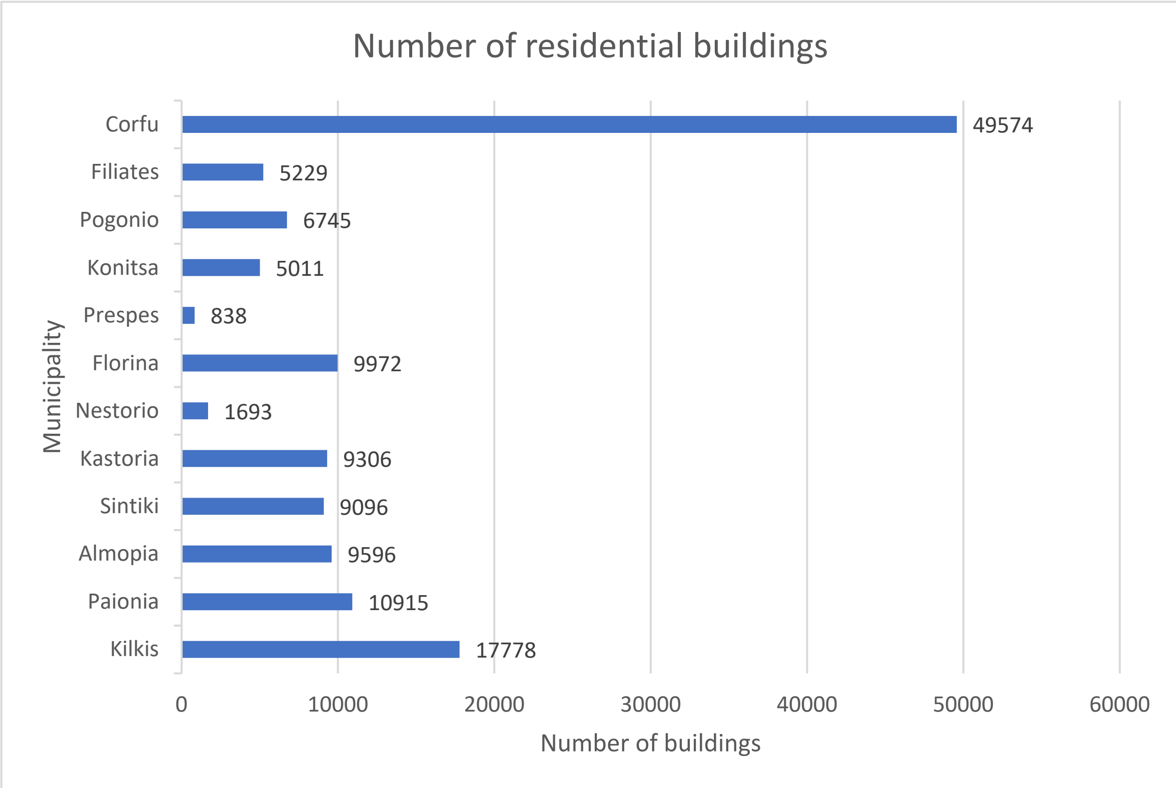


Figure 6. Distribution of residential buildings across the municipalities of the Greek part of the CBR.

The distribution of residential buildings according to material, structural type, code level and building height is given in **Error! Reference source not found.**. Buildings constructed before 1960 are generally assumed to have no or low ductility (CDN–DNO), as they were built without seismic design provisions. Structures from 1960 to 1985 typically comply with early seismic codes and are assumed to have limited ductility (CDL–DUL). Buildings constructed between 1985 and 1995 are designed according to more advanced seismic standards and are considered to have medium ductility (CDM–DUM). Post-1995 constructions follow modern seismic design codes and are assumed to have high ductility (CDH–DUH), providing better energy dissipation and seismic resilience. Regarding the type of Lateral Load-Resisting System, LFINF refers to infilled frames, where masonry infill contributes to lateral stiffness but may behave non-ductile under seismic loads. LDUAL indicates a dual frame-wall system, combining shear walls and frames for improved seismic performance. LFM represents moment-resisting frames, where beams and columns resist lateral forces through flexural action. LWAL denotes wall systems, relying on load-bearing walls or shear walls as the primary lateral resistance. STDRE is dressed stone masonry, characterized by precisely cut stones offering better interlocking and higher strength. CL99 refers to fired clay units of unknown type, indicating standard brick masonry with uncertain mechanical properties and higher vulnerability

The majority of the buildings are constructed either from unreinforced masonry (MUR) or reinforced concrete (RC), are one-to-two story buildings, designed with no or low code level.

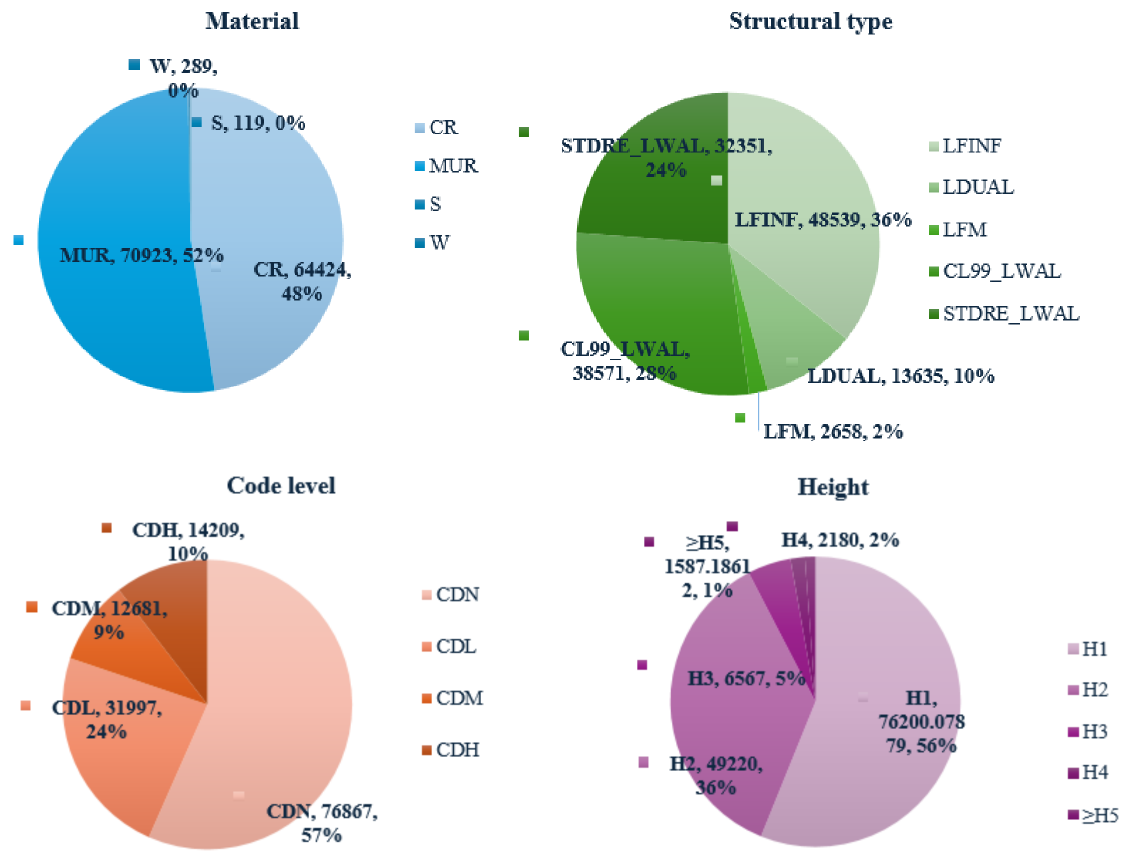


Figure 7. Distribution of residential buildings of the Greek part of the CBR according to material, structural type, code level and building height.

3.2.3 N. Macedonia

The required attributes of the residential building assets are collected for each municipality at the Macedonian side of the CBR and from multiple sources, as indicated below:

- Census 2002 (The State Statistical Office, 2002, MAKSTAT database, PxWeb - Select table)
- Census 2021, (The State Statistical Office, 2002, MAKSTAT database, PxWeb - Select table)
- ESRM20 (Crowley et al, 2021)
- IZIIS data base (ИЗИИС-МСЗ – restricted access)
- Experts' knowledge

The total number of residential buildings is 148,392. Their distribution by municipality is presented in Figure 8. Of these, 91,252 are masonry structures and 57,140 are reinforced concrete buildings, classified into three categories according to design year/ construction period reflecting the evolution of seismic code requirements (Figure 9).

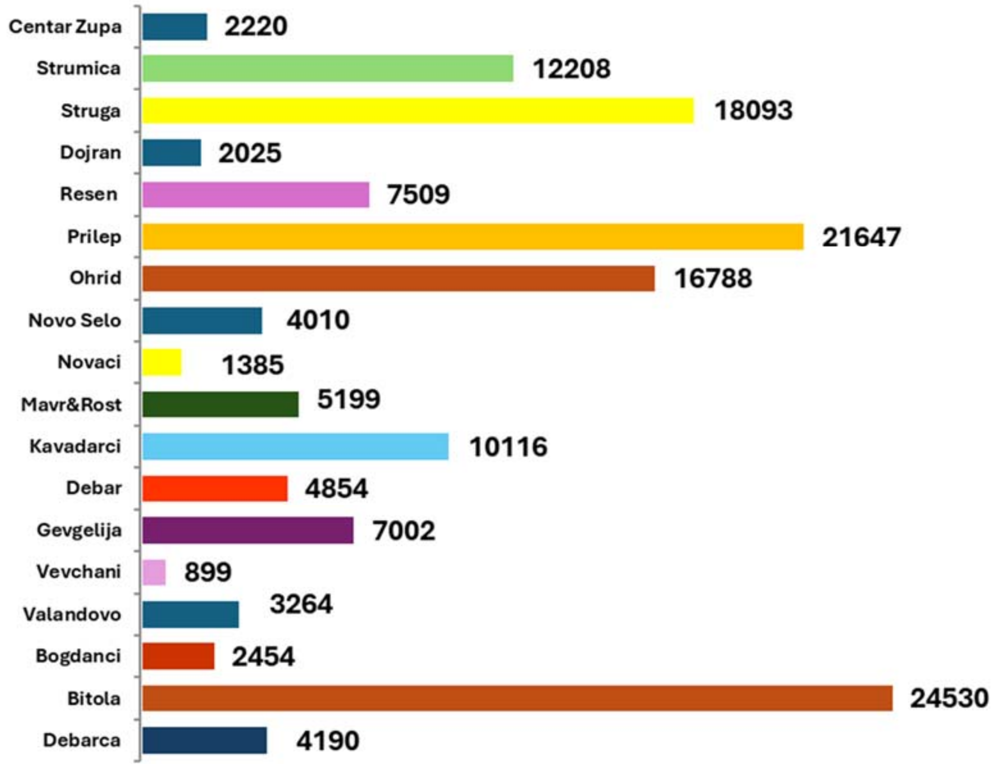


Figure 8.Distribution of residential buildings per municipality

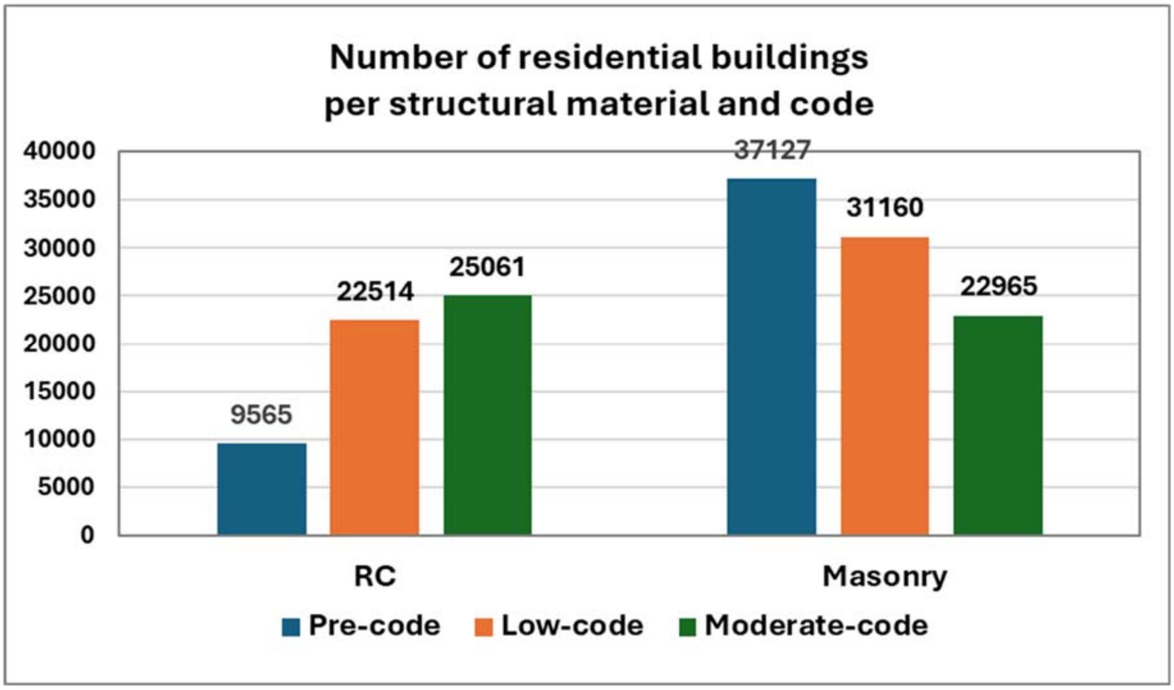


Figure 9. Distribution of residential buildings by structural material and code

3.3. Commercial Buildings

3.3.1. Albania

The required attributes of the commercial building assets are collected for each municipality at the Albanian side of the CBR and generally using the below datasets:

- Open Street Map (https://www.openstreetmap.org)
- Expert knowledge

The total number of commercial buildings is 107. Their distribution by municipality is presented in Figure 10. There is no available data on their construction material or year of construction 11 of these buildings are assumed masonry structures and the rest are assumed as reinforced concrete buildings. All commercial buildings are assumed to be constructed after 1990 and designed with moderate code Figure 11.

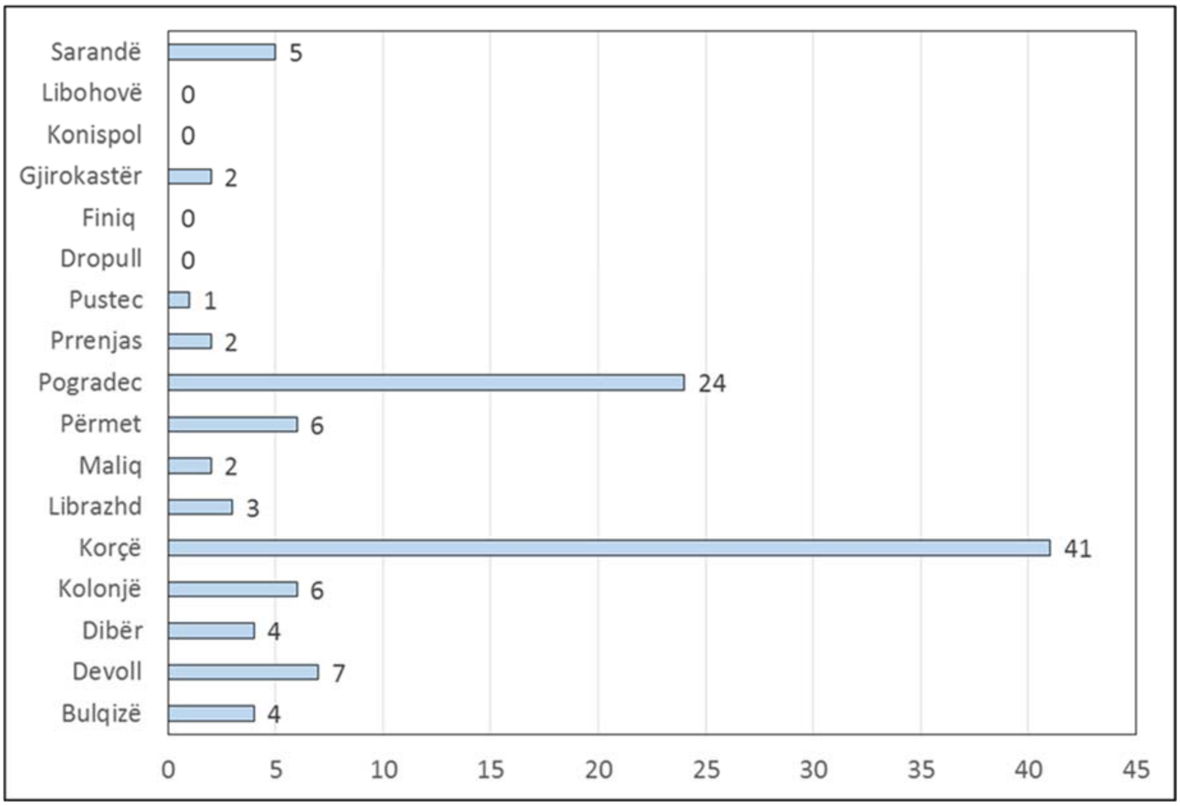


Figure 10. Distribution of commercial buildings per municipality

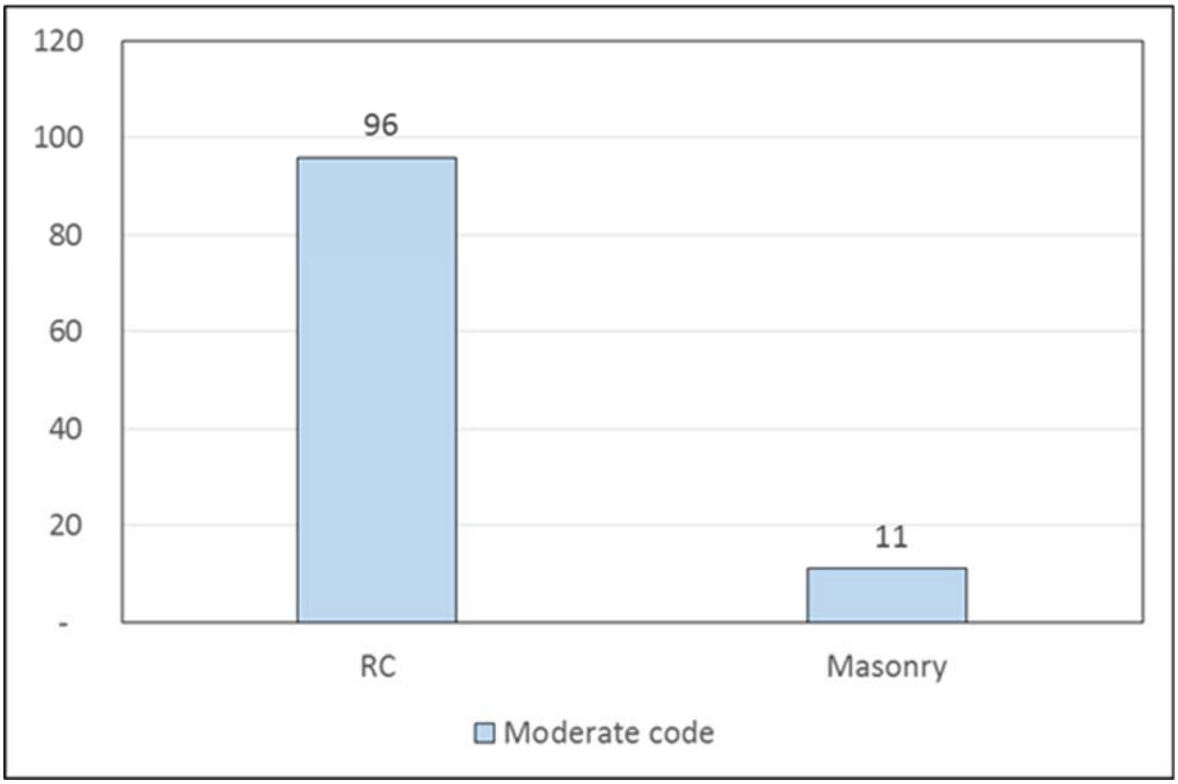


Figure 11. Distribution of commercial buildings by structural material and code

3.3.2 Greece

The herein developed exposure model for the commercial buildings of the Greek part of the CBR is based on the results of the national buildings census of 2011 (ELSTAT 2011). The census includes information on the type of use, main construction material, period of construction, number of stories, type of roof, existence of pilotis (soft storey) and number of residencies. The developed exposure model is aggregated at settlement level and includes a total of 8,201 buildings with exclusive or primary commercial use. These buildings are distributed to the different municipalities of the Greek part of the CBR according to **Error! Reference source not found.**.

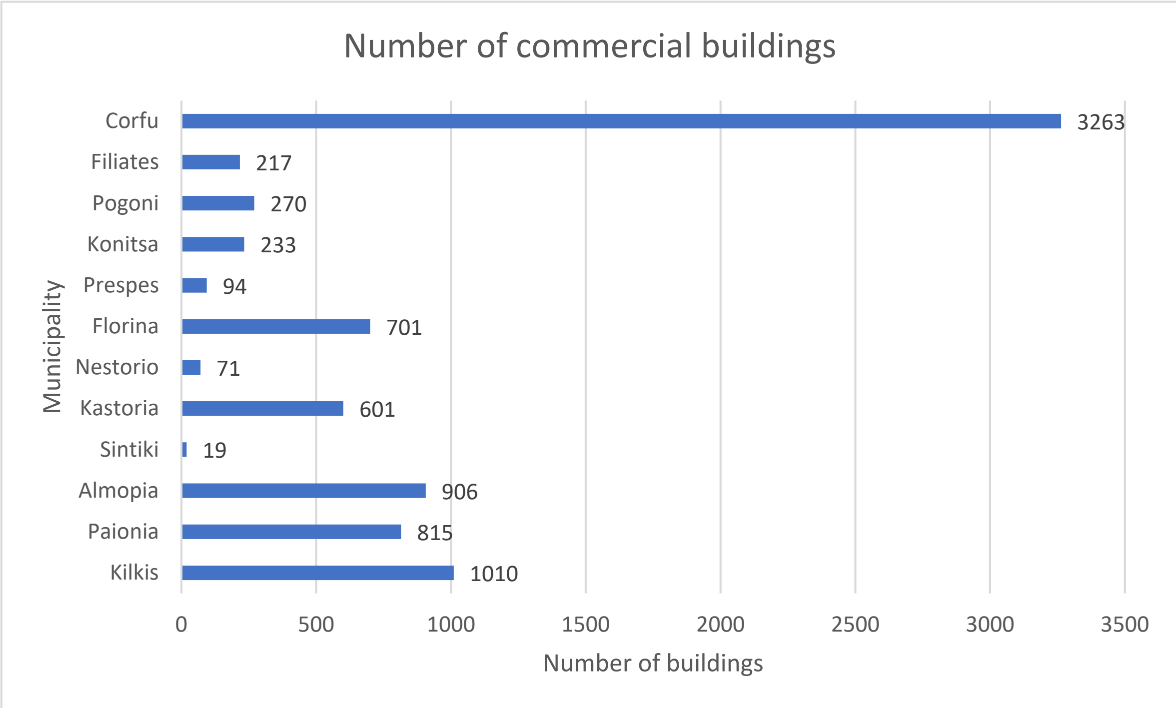


Figure 12. Distribution of commercial buildings across the municipalities of the Greek part of the CBR.

The distribution of commercial buildings according to material, structural type, code level and building height is given in Figure 13. Buildings constructed before 1960 are generally assumed to have no or low ductility (CDN–DNO), as they were built without seismic design provisions. Structures from 1960 to 1985 typically comply with early seismic codes and are assumed to have limited ductility (CDL–DUL). Buildings constructed between 1985 and 1995 are designed according to more advanced seismic standards and are considered to have medium ductility (CDM–DUM). Post-1995 constructions follow modern seismic design codes and are assumed to have high ductility (CDH–DUH), providing better energy dissipation and seismic resilience. Regarding the type of Lateral Load-Resisting System, LFINF refers to infilled frames, where masonry infill contributes to lateral stiffness but may behave non-ductile under seismic loads. LDUAL indicates a dual frame-wall system, combining shear walls and frames for improved seismic performance. LFM represents moment-resisting frames, where beams and columns resist lateral forces through flexural action. LWAL denotes wall systems, relying on load-bearing walls or shear walls as the primary lateral resistance. STDRE is dressed stone masonry, characterized by precisely cut stones offering better interlocking and higher strength. CL99 refers to fired clay units of unknown type, indicating standard brick masonry with uncertain mechanical properties and higher vulnerability

The majority of the buildings are constructed either from unreinforced masonry (MUR) or reinforced concrete (RC), are one-to-two story buildings, designed with no or low code level.

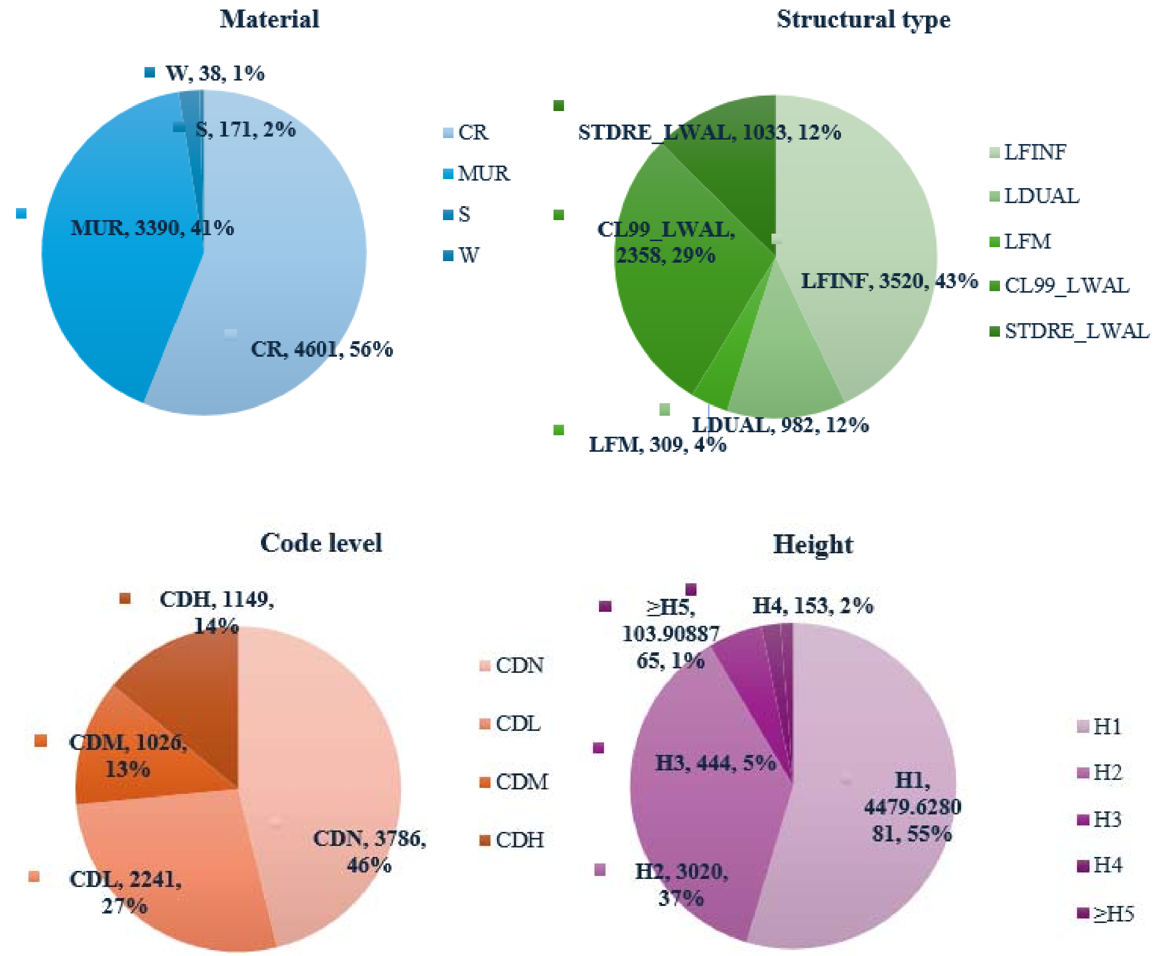


Figure 13. Distribution of commercial buildings of the Greek part of the CBR according to material, structural type, code level and building height.

3.3.3 N. Macedonia

The required attributes of the commercial building assets are collected for each municipality at the Macedonian side of the CBR and generally using the below datasets:

- ESRM20 (Crowley et al, 2021)
- IZIIS data base (ИЗИИС-МСЗ – restricted access)

The total number of commercial buildings is 9929. Their distribution by municipality is presented in Figure 14. Of these, 2,770 are masonry structures, 4,905 are reinforced concrete buildings, 1,423 are steel structures, and 833 are precast buildings. All are classified into three categories based on design year/construction period, reflecting the evolution of seismic code requirements (Figure 15).

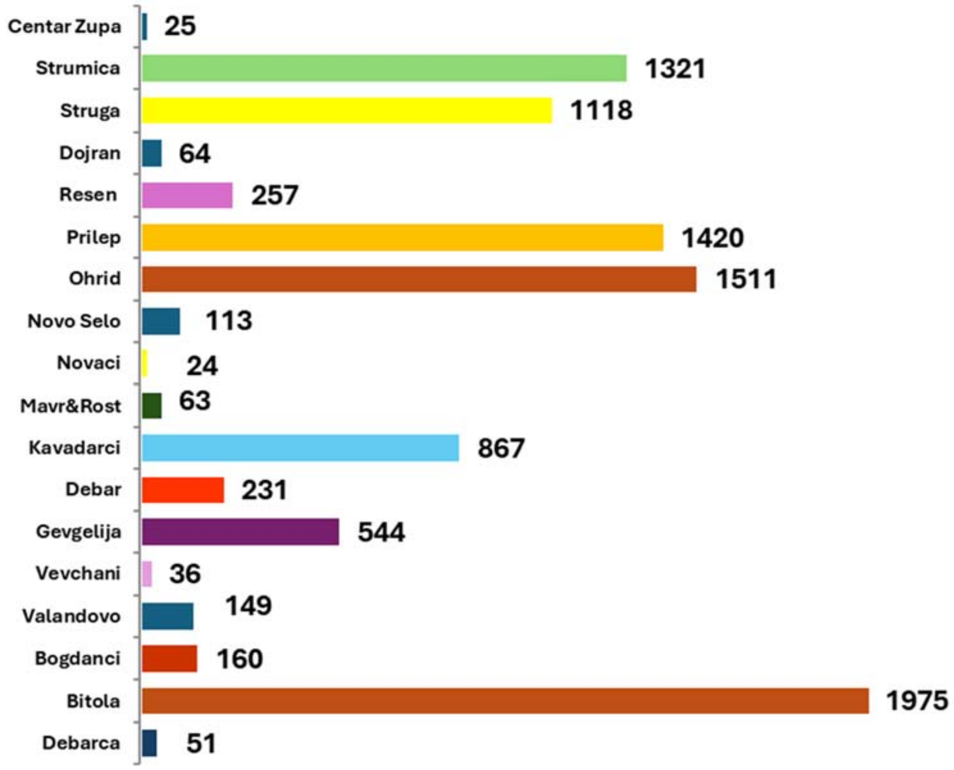


Figure 14.Distribution of commercial buildings per municipality

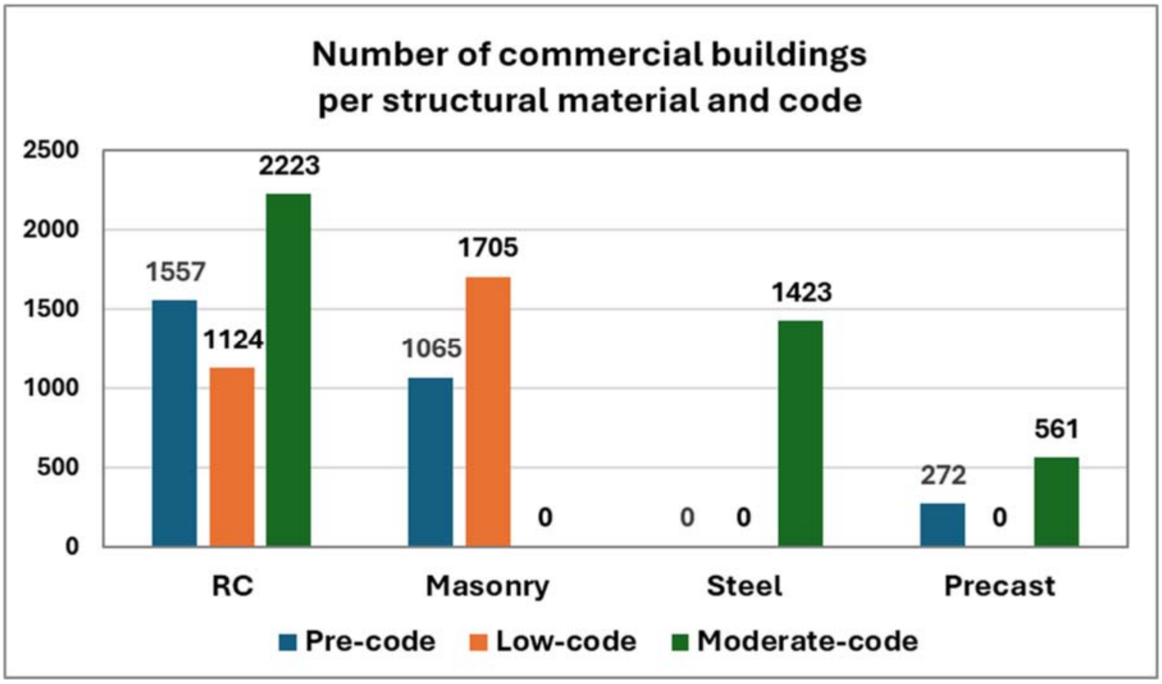


Figure 15. Distribution of commercial buildings by structural material and code

3.4. Industrial Buildings

3.4.1. Albania

The required attributes of the industrial building assets are collected for each municipality at the Albanian side of the CBR and generally using the below datasets:

- Open Street Map (https://www.openstreetmap.org)
- Expert knowledge

The total number of industrial buildings is 100. Their distribution by municipality is presented in Figure 16. There is no specific available data on the construction material and construction period of these buildings on these municipalities. Based on the general knowledge of this building stock, most of these buildings are constructed in the period 1960÷1990, which for residential buildings is considered as low code, and a small amount of these buildings are constructed after 1990. Usually, industrial buildings in Albania in the period 1960÷1990 are constructed with a mixed masonry and reinforced concrete structure, and the materials used for these structure is generally better than those used for residential buildings. Given these reasons, the industrial buildings stock is assumed as 50% masonry structures and 50% RC structures, and all buildings are considered as being designed with moderate code (Figure 17).

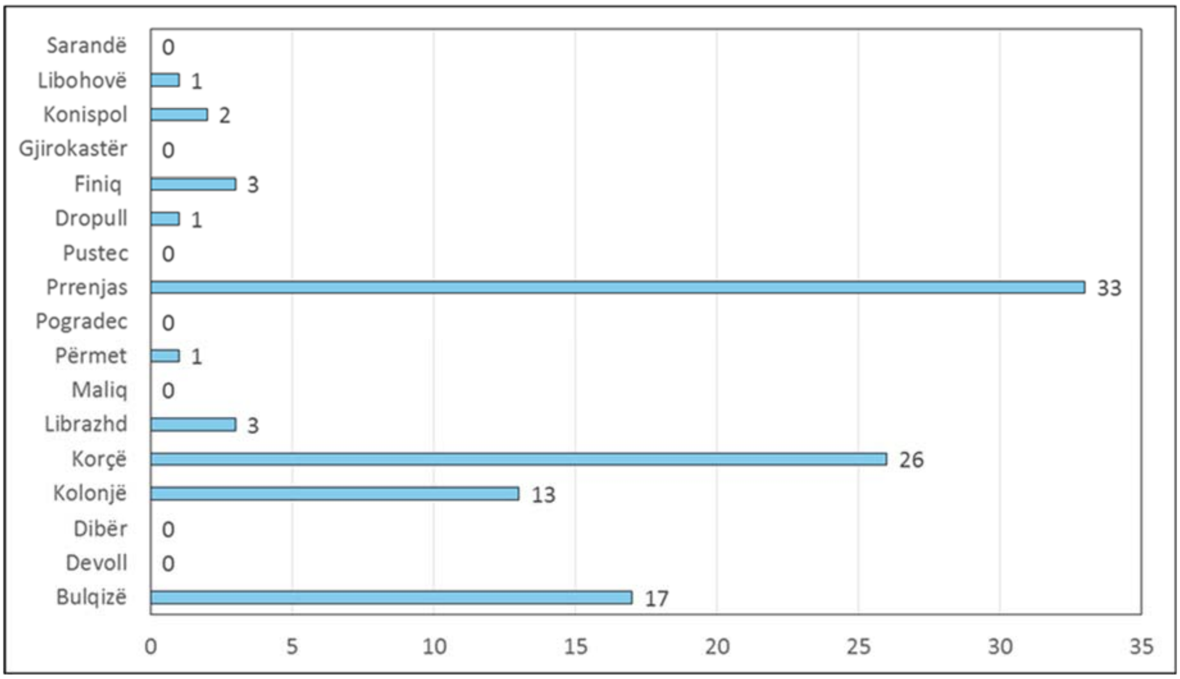


Figure 16. Distribution of industrial buildings per municipality

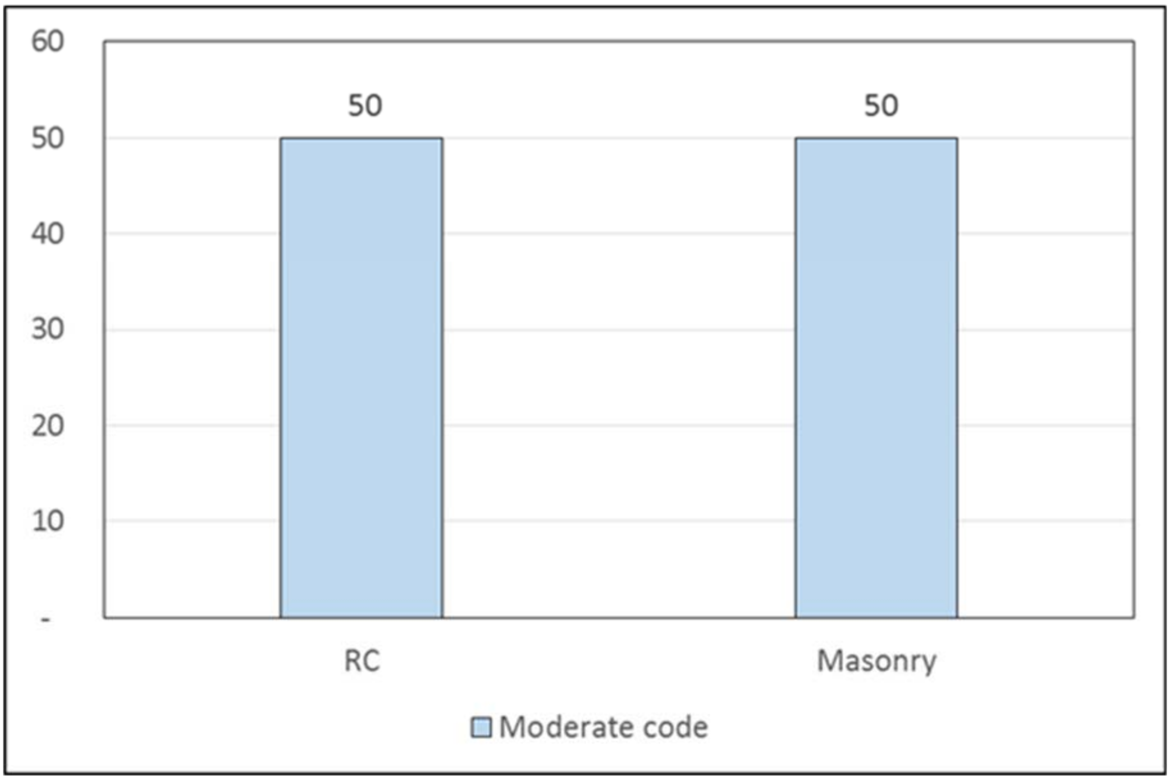


Figure 17. Distribution of industrial buildings by structural material and code

3.4.2 Greece

The herein developed exposure model for the industrial buildings of the Greek part of the CBR is based on the results of the national buildings census of 2011 (ELSTAT 2011). The census includes information on the type of use, main construction material, period of construction, number of stories, type of roof, existence of pilotis (soft story) and number of residencies. The developed exposure model is aggregated at settlement level and includes a total of 1,242 buildings with exclusive or primary industrial use. These buildings are distributed to the different municipalities of the Greek part of the CBR according to Figure 18.

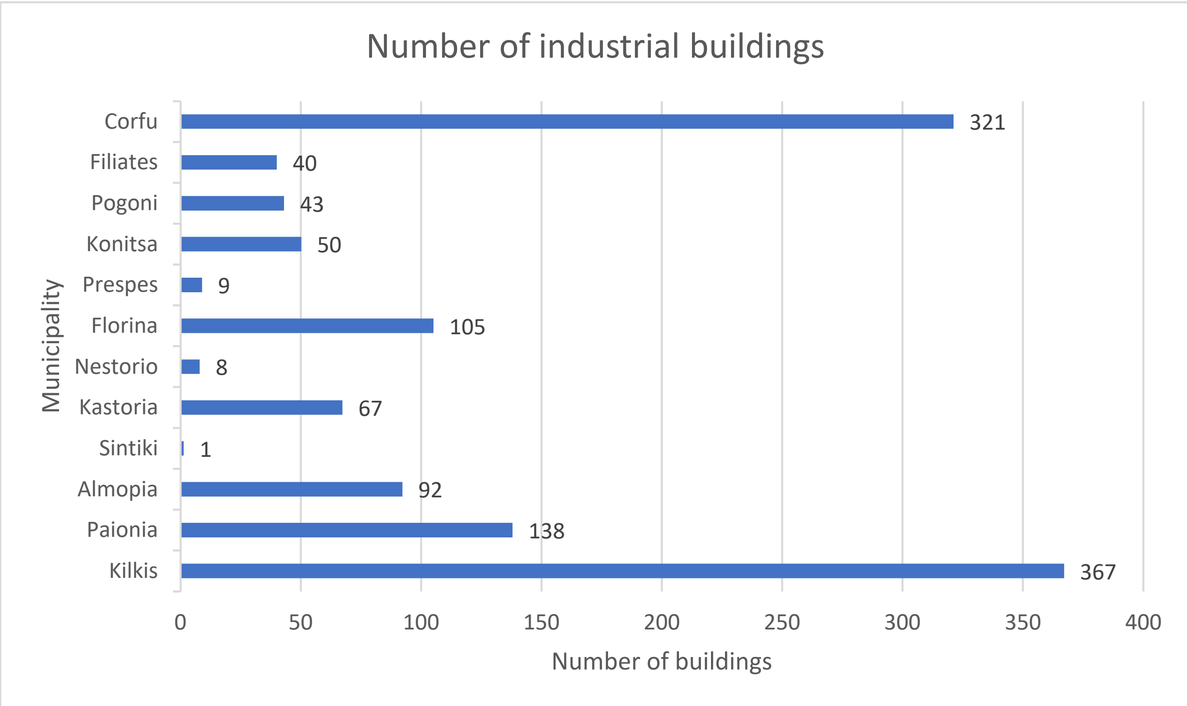


Figure 18. Distribution of industrial buildings across the municipalities of the Greek part of the CBR.

The distribution of industrial buildings according to material, structural type, code level and building height is given in *Figure 19*. Buildings constructed before 1960 are generally assumed to have no or low ductility (CDN–DNO), as they were built without seismic design provisions. Structures from 1960 to 1985 typically comply with early seismic codes and are assumed to have limited ductility (CDL–DUL). Buildings constructed between 1985 and 1995 are designed according to more advanced seismic standards and are considered to have medium ductility (CDM–DUM). Post-1995 constructions follow modern seismic design codes and are assumed to have high ductility (CDH–DUH), providing better energy dissipation and seismic resilience. Regarding the type of Lateral Load-Resisting System, LFINF refers to infilled frames, where masonry infill contributes to lateral stiffness but may behave non-ductile under seismic loads. LDUAL indicates a dual frame-wall system, combining shear walls and frames for improved seismic performance. LFM represents moment-resisting frames, where beams and columns resist lateral forces through flexural action. LWAL denotes wall systems, relying on load-bearing walls or shear walls as the primary lateral resistance. STDRE is dressed stone masonry, characterized by precisely cut stones offering better interlocking and higher strength. CL99 refers to fired clay units of unknown type, indicating standard brick masonry with uncertain mechanical properties and higher vulnerability.

The majority of the buildings are constructed either from unreinforced masonry (MUR) or reinforced concrete (RC), are one-to-two story buildings, designed with no or low code level.

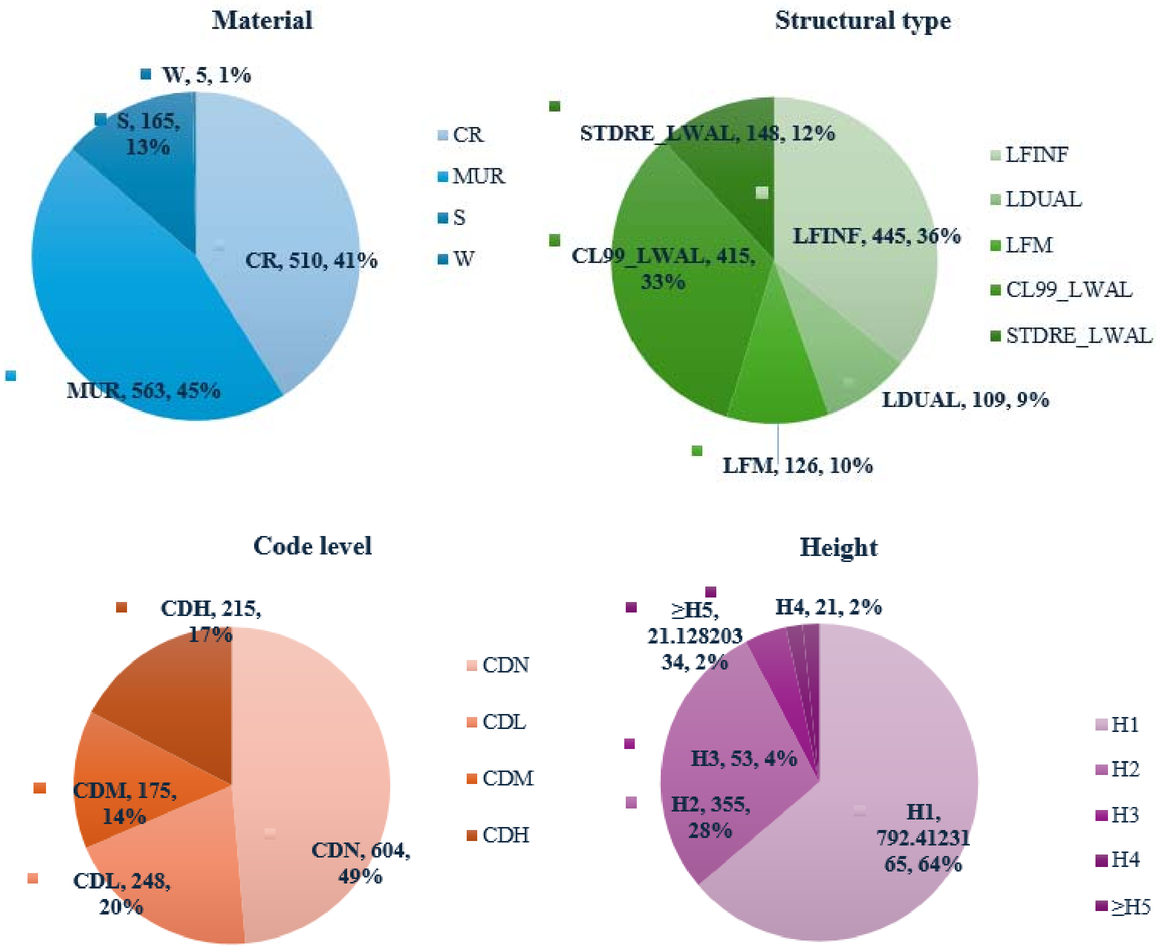


Figure 19. Distribution of industrial buildings of the Greek part of the CBR according to material, structural type, code level and building height.

3.4.3 N. Macedonia

The required attributes of the industrial building assets are collected for each municipality at the Macedonian side of the CBR and generally using the below datasets:

- ESRM20 (Crowley et al, 2021)
- IZIIS data base (ИЗИИС-МСЗ – restricted access)

The total number of industrial buildings is 4323. Their distribution by municipality is presented in Figure 20. Of these, 547 are masonry structures, 2045 are reinforced concrete buildings, 1121 are steel structures, 439 are precast structures and 172 are steel-concrete buildings. All are classified into three categories based on design year/construction period, reflecting the evolution of seismic code requirements (Figure 21).

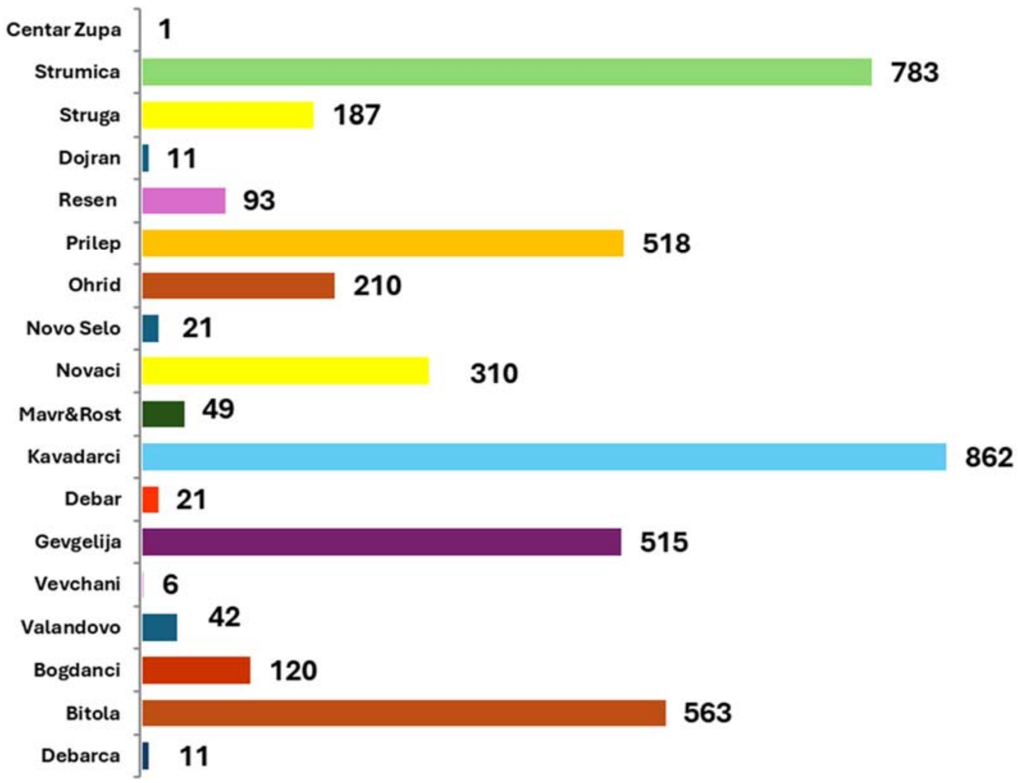


Figure 20. Distribution of industrial buildings per municipality

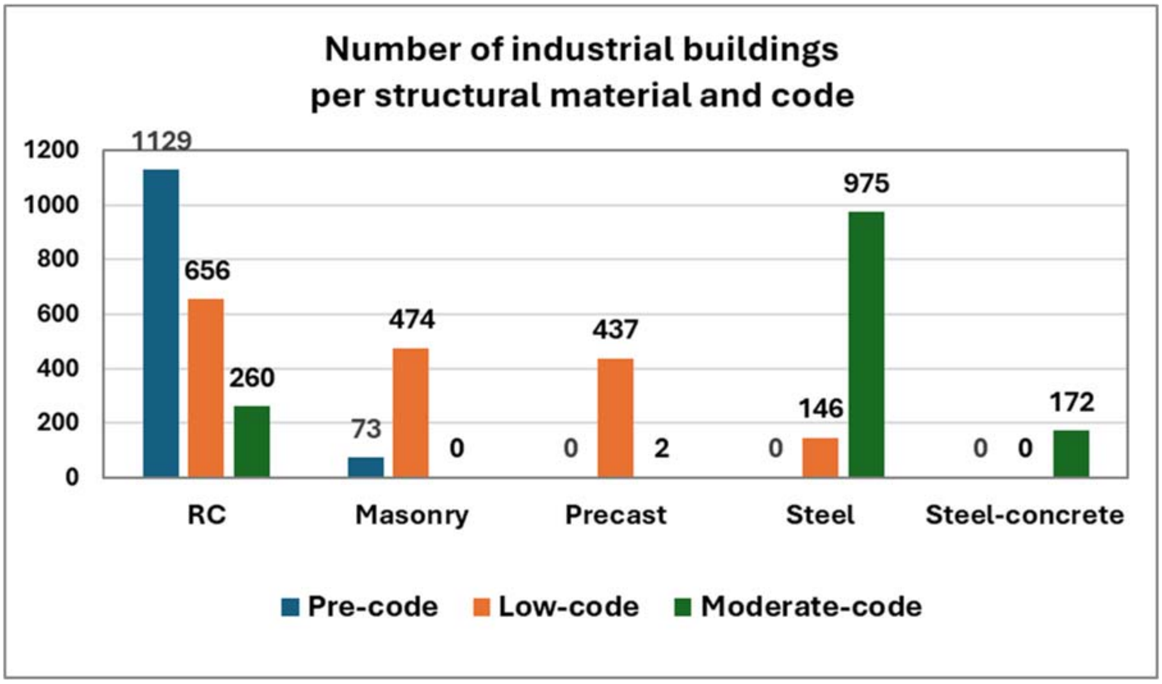


Figure 21. Distribution of industrial buildings by structural material and code

4. Fragility models for assessing seismic vulnerability of residential, commercial and industrial buildings

This section provides the main features of the fragility models adopted for assessing the vulnerability of residential, commercial, and industrial buildings located within the CBR, presented in Section 3 above.

Seismic vulnerability of the exposure models for above buildings assets in CBR, is assessed in accordance with the CRISIS D4.2 (2022) methodology and the updated SP-BELA fragility curves (Borzi et al., 2008; Faravelli et al., 2023).

This approach enables a consistent classification of the assessed RC structures according to their seismic design level, namely:

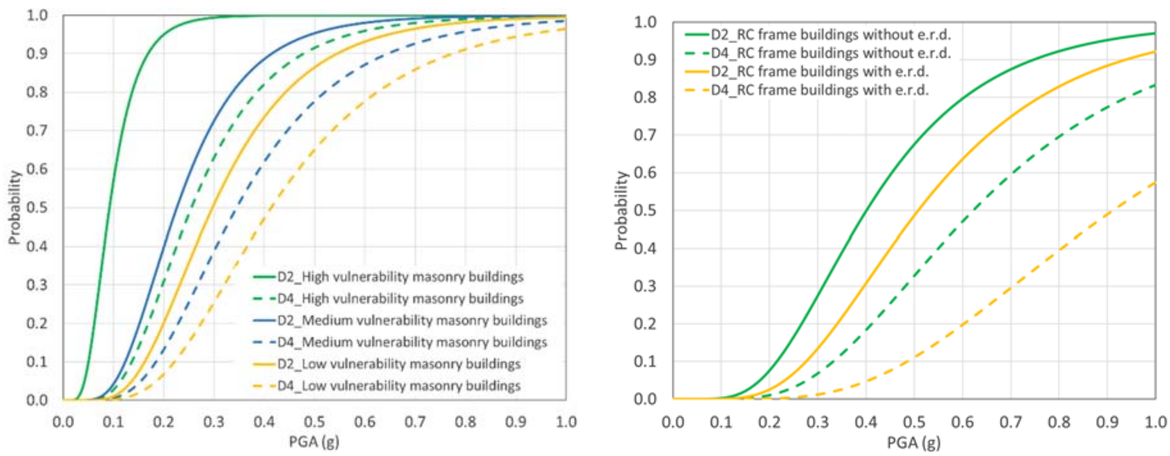
- non–earthquake-resistant design buildings
- earthquake-resistant design buildings

For masonry structures, three categories are defined, correlated are correlated with the five different construction periods.

- High-vulnerability masonry structures
- Medium-vulnerability masonry structures
- Low-vulnerability masonry structures
-

Expert knowledge was applied to reorganize the existing exposure model in order to align it with the classification defined in the recent work of Faravelli et al. (2023). This ensures consistency with the two categories of earthquake-resistant design for reinforced concrete buildings and the three established vulnerability levels for masonry structures. The SP-BELA fragility functions provide an empirically calibrated relationship between structural damage probability and ground motion intensity expressed via PGA. Figure 22 shows the adopted fragility curves for two-story masonry and three-story reinforced concrete buildings.

Furthermore, the corresponding fragility parameters for RC and masonry RC buildings with one, two, three, and four stories are summarized in Table 2. These parameters serve as the fundamental input for the subsequent seismic vulnerability assessment.



(a) (b)

Figure 22. Fragility curves of 2-storey masonry (a) and 3 -storey RC buildings (b) (Faravelli, 2023)

Table 2. Fragility curve parameters (median and β) for five damage levels for reinforced concrete and masonry structures by number of storeys

Typology	N. of storeys	α_{D1} (g)	β_{D1} (−)	α_{D2} (g)	β_{D2} (−)	α_{D3} (g)	β_{D3} (−)	α_{D4} (g)	β_{D4} (−)	α_{D5} (g)	β_{D5} (−)
High vulnerability masonry buildings	1	0.053	0.603	0.145	0.603	0.210	0.603	0.389	0.580	0.486	0.580
	2	0.033	0.473	0.092	0.473	0.133	0.473	0.255	0.489	0.319	0.489
	3	0.030	0.519	0.083	0.519	0.121	0.519	0.225	0.531	0.282	0.531
	≥4	0.030	0.506	0.082	0.506	0.120	0.506	0.219	0.516	0.273	0.516
Medium vulnerability masonry buildings	1	0.202	0.603	0.358	0.603	0.404	0.603	0.525	0.580	0.750	0.580
	2	0.128	0.473	0.226	0.473	0.256	0.473	0.345	0.489	0.493	0.489
	3	0.116	0.519	0.205	0.519	0.232	0.519	0.304	0.531	0.434	0.531
	≥4	0.115	0.506	0.204	0.506	0.230	0.506	0.295	0.516	0.422	0.516
Low vulnerability masonry buildings	1	0.309	0.603	0.469	0.603	0.526	0.603	0.630	0.580	1.050	0.580
	2	0.196	0.473	0.297	0.473	0.332	0.473	0.414	0.489	0.690	0.489
	3	0.177	0.519	0.269	0.519	0.301	0.519	0.365	0.531	0.608	0.531
	≥4	0.176	0.506	0.267	0.506	0.299	0.506	0.354	0.516	0.591	0.516
RC frame buildings without e.r.d.	1	0.522	0.642	1.741	0.642	2.350	0.642	2.474	0.636	3.535	0.636
	2	0.179	0.515	0.597	0.515	0.807	0.515	0.889	0.511	1.269	0.511
	3	0.120	0.486	0.401	0.486	0.542	0.486	0.622	0.490	0.889	0.490
	≥4	0.110	0.498	0.368	0.498	0.496	0.498	0.611	0.528	0.873	0.528
RC frame buildings with e.r.d.	1	1.369	0.624	1.685	0.624	2.190	0.624	2.391	0.616	4.782	0.616
	2	0.535	0.507	0.658	0.507	0.855	0.507	1.026	0.498	2.053	0.498
	3	0.413	0.477	0.508	0.477	0.661	0.477	0.912	0.492	1.824	0.492
	≥4	0.386	0.476	0.475	0.476	0.618	0.476	0.935	0.499	1.871	0.499

5. Concluding remarks

The following points summarize the harmonised CBR risk exposure model for residential, commercial and industrial buildings, along with the corresponding fragility curves:

- The building inventory is done exclusively from available national datasets—such as statistical office records, census data, European Seismic Risk Model - ESRM20 (Crowley et al, 2021), relevant projects, studies, documentation and other publicly available sources of information, at municipality level —and does not involve any field investigations.

- For the CBR area between North Macedonia, Greece, and Albania, the following assets have been mapped:

  - 399022 residential buildings (148,392 in North Macedonia; 135,755 in Greece; 114,875 in Albania)
  - 18,237 commercial buildings (9,929 in North Macedonia; 8,201 in Greece; 107 in Albania)
  - 5666 industrial (4,324 in North Macedonia; 1,242 in Greece; 100 in Albania)

- Fragility models for assessing seismic vulnerability of residential, commercial and industrial buildings are cross-border harmonized and based on CRISIS D4.2 (2022) methodology and the updated SP-BELA fragility curves (Borzi et al., 2008; Faravelli et al., 2023).

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