European Commission

JRC TECHNICAL REPORTS

Framework for resilience analysis of EU buildings

Tsionis, G; Sousa, ML; Palermo, V; Maio R

2017

Joint Research Centre

EUR 29053 EN

Contact information
Name: Georgios Tsionis
Address: Joint Research Centre, Via E. Fermi 2749, Ispra (VA) 21027, Italy
Email: georgios.tsionis@ec.europa.eu
Tel.: +39 03 32 78 94 84

JRC Science Hub
https://ec.europa.eu/jrc

JRC110165

EUR 29053 EN

PDF	ISBN 978-92-79-77703-5	ISSN 1831-9424	doi:10.2760/923762

Luxembourg: Publications Office of the European Union, 2017

How to cite this report: Tsionis G, Sousa ML, Palermo V, Maio R; *Framework for resilience analysis of EU buildings*, EUR 29053 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-77703-5, doi:10.2760/923762, PUBSY No. 110165

Contents

Abstract

This report summarises the activities of the JRC institutional work package related to the resilience of the European building stock. It covers the fundamental components of seismic risk assessment studies, namely hazard (national design codes and recent research results), exposure (inventory of the European building stock) and vulnerability (fragility curves for reinforced concrete and masonry buildings). In addition, the report examines the resilience of the built environment with focus on the modelling of the post-event recovery process. Lastly, a workplan to integrate these components for the analysis of the resilience of the European building stock is put forward.

1 Introduction

Increased resilience is a strategic objective of the European strategy for disaster management[1], which calls for a qualitative shift from reacting to emergencies to a more proactive role of prevention and preparedness. Besides, prevention is more cost-effective and can be a driver for economic growth and is attracting more attention as part of the disaster risk management cycle in the relevant European policies.[2] Furthermore, the protection and refurbishment of urban areas deserves particular attention[3], owing to their potential for economic growth – 67 % of Europe's GDP is generated in metropolitan areas – and energy efficiency in the transport and housing sector, as well as because of their high vulnerability to natural and man-made disasters.

Observations show that in recent decades there was a solid increase of economic losses due to earthquakes, although seismic hazard levels revealed no significant variation (Coburn and Spence 2002). Across the world, in urban areas prone to earthquakes, several aggravating factors regarding seismic losses may be identified. Firstly, in developed countries, the growth of economic losses may be attributed to the increase of exposure due to the concentration of population and to the complexity of urban systems (Gioncu and Mazzolani 2001; FEMA 2008), but also to the substantial vulnerability of an aged building stock. Secondly, in developing countries, the steady increase of seismic losses, both human and economic, may be credited, among others, to overcrowding, to rapid and unplanned urbanization, to poor construction technics and to the non-implementation of modern seismic standards.

In the global context, the Sendai Framework (UNISDR 2015) aims to prevent new and substantially reduce existing disaster risk and losses, applying measures such as the reduction of vulnerability and exposure, and dealing with risk drivers like, for instance, poor land management, non-risk-informed policies, lack of regulation, etc. In addition, inclusive, safe, resilient and sustainable cities feature among the Sustainable Development Goals[4] set by the United Nations.

Keeping the above in mind, an institutional activity was launched at the Joint Research Centre. It deals with the resilience of the buildings in urban areas across the European Union, with focus on regions of moderate-to-high seismicity. The objective is to provide scientific support for decision-making as regards, at the first step, the seismic retrofit of existing buildings. The second stage of the project will examine the scope, synergies and conflicts in retrofitting the building stock for the dual purpose of improving their environmental and seismic performance, the former mainly related to energy consumption.

This report summarises the activities related to the resilience of the European building stock. It covers the fundamental components of seismic risk assessment studies, namely hazard (Chapter 2 – national design codes and recent research results), exposure (Chapter 3 – inventory of the European building stock) and vulnerability (Chapter 4 – fragility curves for reinforced concrete and masonry buildings). In addition, the report examines the resilience of the built environment with focus on the modelling of the post-event recovery process (Chapter 5). Lastly, a work plan to integrate these components for the analysis of the resilience of the European building stock is put forward.

[1] Communication from the Commission to the European Parliament and the Council. Towards a stronger European disaster response: the role of civil protection and humanitarian assistance. COM(2010) 600 final

[2] Communication from the Commission to the European Parliament, the Council and the Committee of the Regions. Strengthening EU Disaster Management: rescEU - Solidarity with Responsibility. COM(2017) 773 final

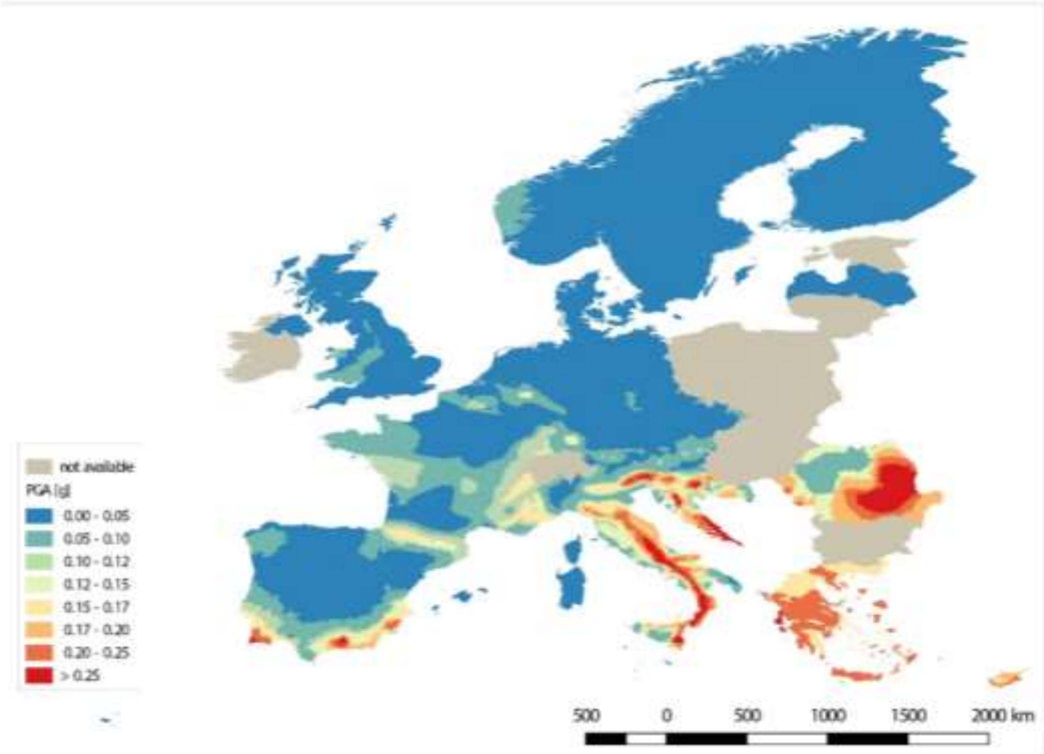
[3] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The urban dimension of EU policies – key features of an EU urban agenda. COM(2014) 490 final

[4] www.un.org/sustainabledevelopment/sustainable-development-goals

2 Seismic hazard in Europe

For the representation of the seismic action, Eurocode 8 (CEN 2004) employs elastic response spectra anchored at the design value of the ground acceleration. Figure 1 presents a map with the reference values of peak ground acceleration for the reference return period for the no-collapse requirement. The values of peak ground acceleration were obtained from the National Annexes to Part 1 of Eurocode 8. The reference return period is 475 years for all countries, except for Romania and the United Kingdom that adopted return periods of 100 and 2500 years, respectively. Seismic action for Type 1 spectrum is shown in the map for Portugal, since this country published two seismic zone maps in its National Annex of Eurocode 8. The regions with the highest values of peak ground acceleration are almost the entire territory of Croatia, Cyprus, Greece, Italy, Slovenia and Romania and parts of France, Spain and Portugal. Note that Figure 1 presents the values of peak ground acceleration at a geographic discretisation that corresponds to municipalities.

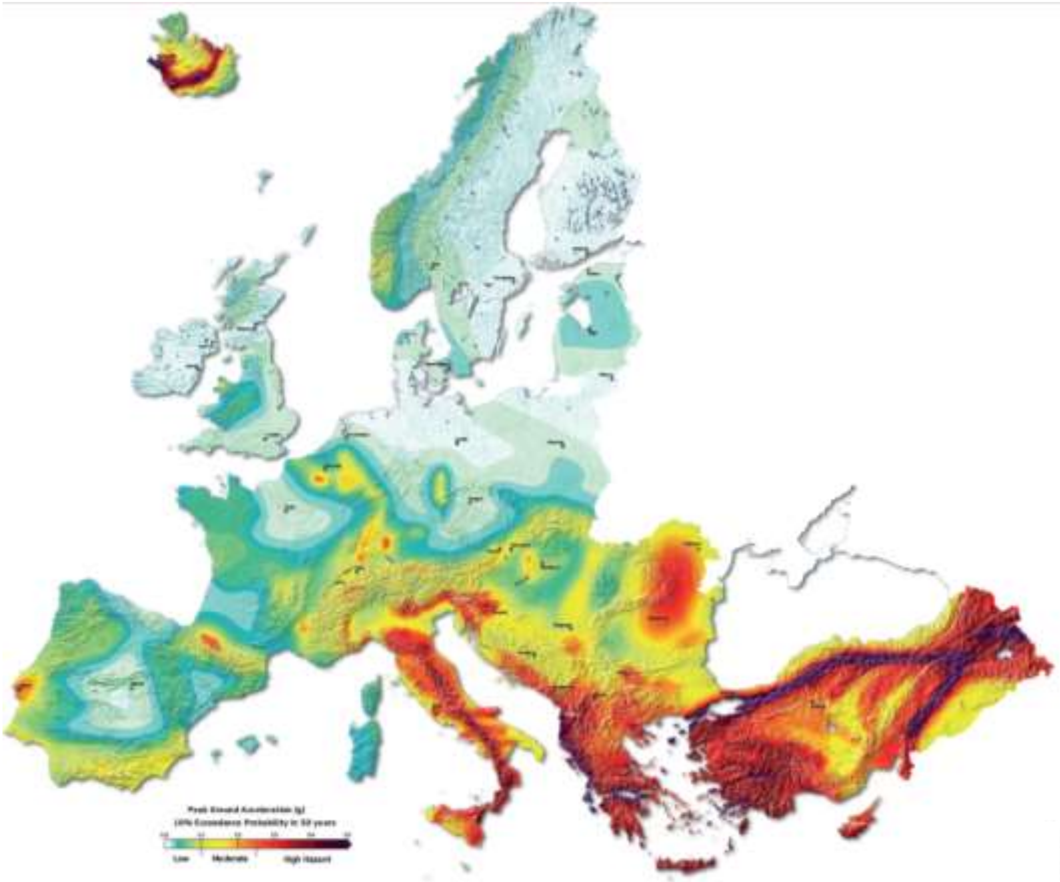
Figure 1. Reference peak ground acceleration (g) for the reference return period of seismic action for the no-collapse requirement in Eurocode 8 (Palermo et al 2018)



The 2013 seismic hazard model for Europe (Woessner et al 2015) is presented in Figure 2 that maps the values of peak ground acceleration with 10 % probability of exceedance in 50 years. This hazard model was produced within the SHARE European research project and encompasses a number of improvements with respect to previous models, such as a comprehensive catalogue of earthquakes and seismic faults, independent seismogenic models, models for maximum magnitude, accounting for epistemic uncertainties of model components and hazard results, etc.

From the comparison of Figure 1 and Figure 2, it appears that the two maps provide a very similar geographical distribution of low, moderate and high seismic hazard among the different countries. However, the specific values of peak ground acceleration at a given location may vary significantly. It is noted that the SHARE results do not replace the existing national design regulations and seismic provisions, which must be obeyed for the design and construction of buildings.

Figure 2. SHARE seismic hazard map for peak ground acceleration with 10 % probability of exceedance in 50 years, adapted from Giardini et al (2013)



3 Exposure of the European building stock

3.1 Exposure data in Europe

There are three main sources of information on the European building stock. The first two were developed for research purposes on the seismic risk assessment and the energy efficiency in different climatic zones. The third source of data are the national censuses that collect, at regular intervals, information on buildings or conventional dwellings – albeit not completely harmonised across countries.

In the framework of the Prompt Assessment of Global Earthquakes for Response (PAGER) system, a global building inventory has been compiled, based on harmonised data from various sources (Jaiswal et al 2010). The inventory provides estimates of the fractions of building types present in urban and rural regions of each country by their functional use. Building types refer to construction material, structural system, height and seismic design in the case of reinforced concrete buildings. A similar objective was pursued in the framework of the NERA European research project, based on the housing census data in the European countries (Crowley et al 2010). The Global Exposure Database developed by the Global Earthquake Model (GEM) Foundation (Gamba 2014) is structured at four different levels: country, region, local and building.

On the other hand, Europe-wide building inventories have been developed for monitoring and improving the energy performance of buildings. Data is usually extracted from previous projects and official statistics, or based on expert estimations in cases where official data is not available. The data of interest for seismic risk assessment include the total number or percentage of buildings (or dwellings) and the total floor area by use of the building, period of construction and material of construction. The information is usually aggregated in large areas that encompass several regions and in most cases refers to a limited number of European countries.

A review of several data sources revealed divergences and incongruities among them, which raise questions on their aptness for use in the seismic loss estimation at large regions (Tsionis 2015). The inconsistencies in the data are reflected in the results of the risk assessment. For instance, Spence et al (2012) used the data from PAGER and NERA to perform a simplified calculation of the expected damage in a number of cities across Europe. The obtained results showed notable differences in the damage estimates using the two databases.

Finally, a population and housing census takes place every 10 years in the member countries of the European Union and the European Free Trade Association. Among the parameters of interest for seismic risk assessment, the period of construction is available in all countries. As shown in Figure 3, data on the construction material and number of floors are recorded in most earthquake-prone areas of Europe, i.e. the majority of Mediterranean and Balkan countries and many of the countries in central and central-east Europe.

Figure 3. Countries where information on the construction material (left) and number of floors (right) was collected at the 2011 building censuses (Tsionis 2015)

3.2 Data from Eurostat Census Hub

Eurostat, i.e. the statistical office of the European Union, provides online high-quality statistics for Europe on several topics, characterised by homogeneity in terms of data collection procedures and outputs. The online tool Census Hub, which provides data regarding the 2011 Census for the whole Europe, has been used within the framework of this study. The data collected from the Census Hub were the number of dwellings by the period of construction at the NUTS3 geographical level. The Nomenclature of Territorial Units for Statistics (NUTS) was formulated to divide the economic territory of the European Union into uniform territorial units to be used for statistical questions (Eurostat 2015). The territory is classified in three hierarchical levels: NUTS1 that groups a set of regions, which in turn are subdivided into NUTS2, comprising groups of districts and then are divided further divided into NUTS3 regions, corresponding to a district level. The NUTS are complemented at the lower level by Local Administrative Units (LAU).

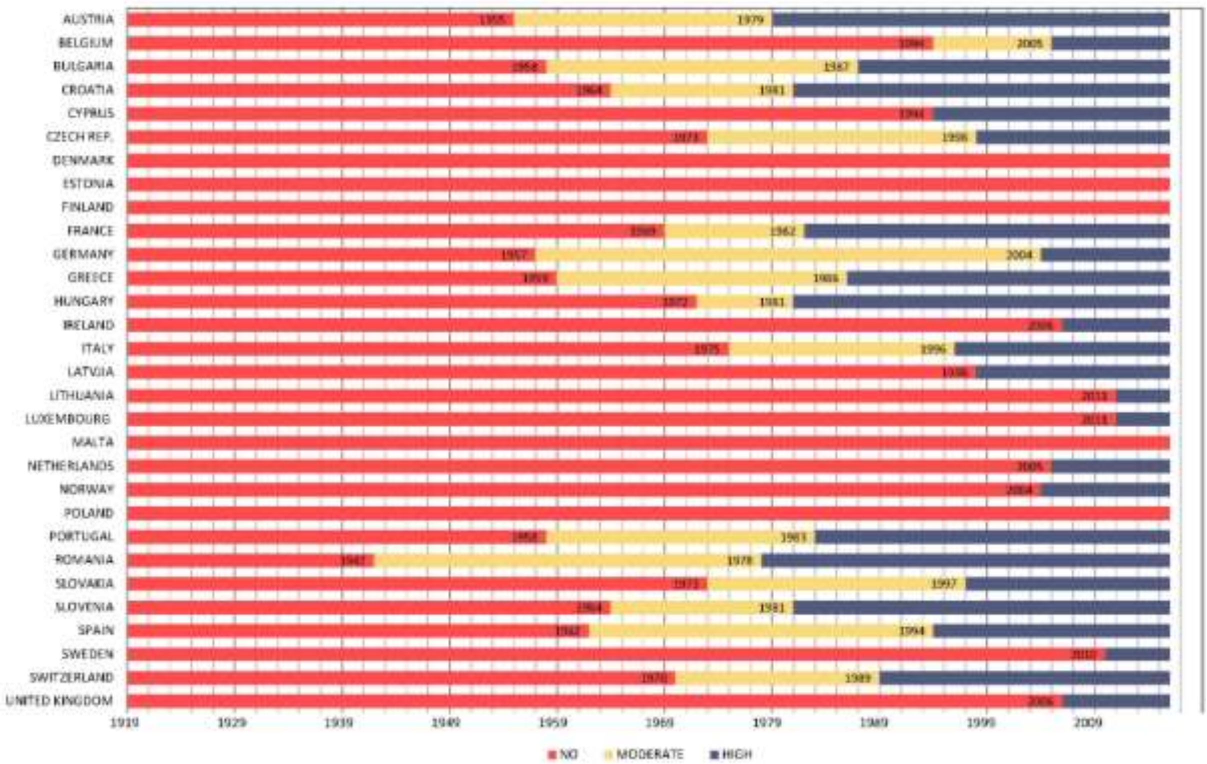
The data were collected and organised in a database for the 28 EU member countries plus Norway and Switzerland. The database consists of several fields like the code and name of NUTS3 per country, the total number of dwellings, the number of dwellings per period of construction and per type of building, and the population. In total, 1 395 NUTS3 regions across Europe are included in the database. Moreover, the inventory was georeferenced and integrated into a Geographic Information System.

3.3 Seismic vulnerability classification of buildings

Dwellings were arranged in different classes of vulnerability, based on the seismic design code that was in force in each country in the year the building was constructed. While a commonly accepted classification of the seismic codes in all European countries is not available, a comprehensive review of all codes (in several languages) and of the differences between consecutive versions is a task beyond the scope of the present study. The evolution of the building codes in the 30 countries was investigated on the basis of the information retrieved in the technical literature regarding i) the entry in force of building / seismic design codes in the different countries and ii) the expected seismic performance of buildings designed in a given time period. An additional assumption was that all the buildings were designed and constructed in compliance with the requirements of the applicable seismic code.

Figure 4 presents the time periods that are considered in this work for the three levels of seismic design (no provisions for earthquake resistance, moderate-level seismic code and high-level seismic code) in the different countries and for the associated classification of the seismic vulnerability of buildings. It may be highlighted that the countries with no code provisions and the ones that only recently improved the provisions for seismic design are those where the seismic hazard is low (see Figure 1 and Figure 2). On the contrary, the countries where the seismic hazard levels are higher are at the forefront of a process of updating the design codes for earthquake resistance of buildings.

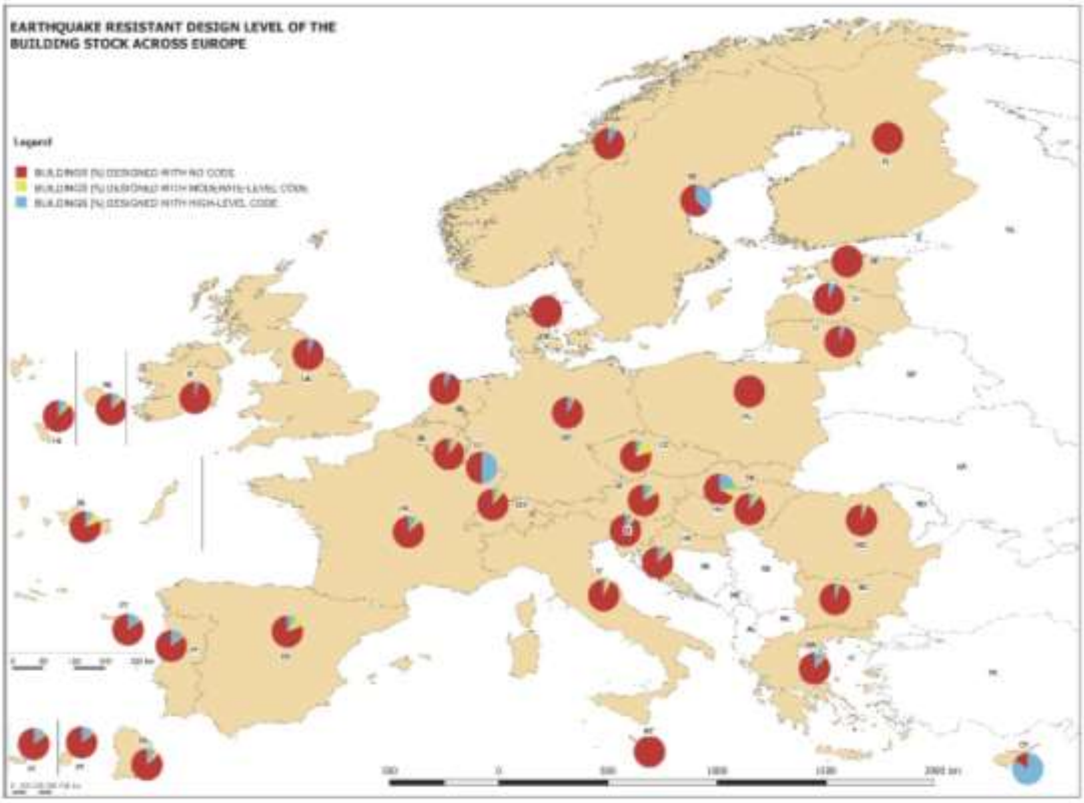
Figure 4. Evolution of seismic design codes in the European countries (Palermo et al 2018)



Following the investigation of the seismic codes of each country, a harmonised classification of the seismic vulnerability of the building stock across Europe is proposed. This classification does not account for other characteristics of buildings – height, construction material and structural system – that are important for the seismic response. It is noted that reliable information on these parameters is only available for some countries and often not for all three parameters in the same country. Based on this classification, the database was complemented with the following fields: number and percentage of dwellings per vulnerability class, and the vulnerability class of the majority of dwellings in each NUTS3.

The results of this classification confirm that the European building stock is old and show that the large majority of buildings across Europe was constructed before the date of entry into force of the first building codes with rules for seismic design. Figure 5 in particular presents the percentage of dwellings in buildings without seismic design and with moderate-level seismic design. A comparison of Figure 1 and Figure 5 may lead to the conclusion that a significant percentage of the buildings in the European countries of moderate and high earthquake hazard require upgrading of their seismic resistance. Further details on the building inventory are available in Palermo et al (2018).

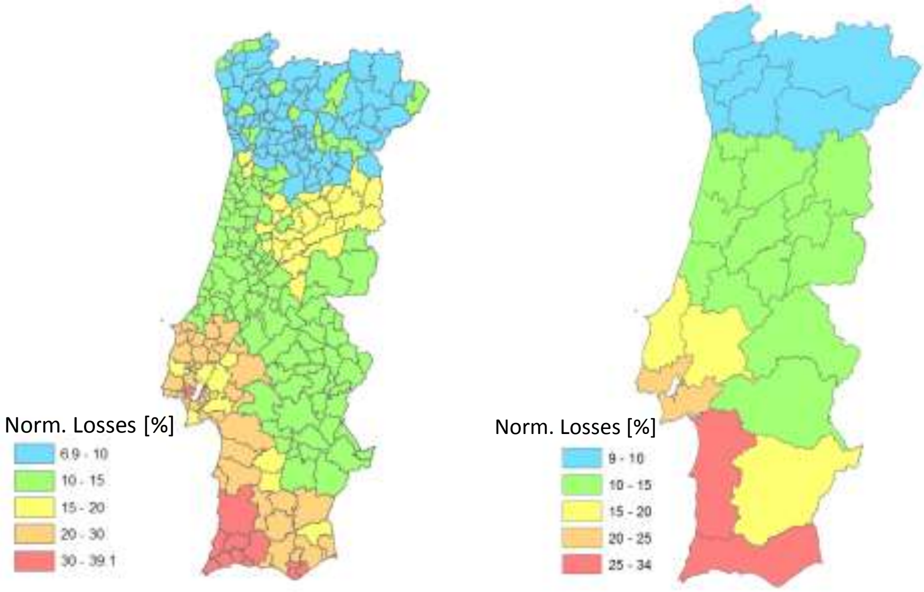
Figure 5. Percentage of buildings designed without provisions for earthquake resistance (no code), moderate level and high-level seismic code, © EuroGeographics for the administrative boundaries



3.4 Effect of the detail of exposure data in large-scale seismic risk assessment

A case study was performed to examine the influence of the level of detail of the datasets of the building stock on the results of large-scale risk assessment studies applied to urban areas in earthquake-prone regions of Europe (Sousa et al 2017). It consisted in a quantitative risk analysis using i) a dataset of exposed residential buildings in Portugal with a high level of geographic detail and ii) the more generic dataset of exposed buildings from the Eurostat Census Hub. Losses were computed for the seismic hazard scenario corresponding to the seismic zoning map adopted in the National Annex to Eurocode 8. Damage to reinforced concrete and masonry buildings was modelled by means of fragility curves that have been recently produced considering the specific characteristics of Portuguese buildings (Silva et al 2015a, Silva et al 2015b). As shown in Figure 6, the assessment based on the generic data captures the order of magnitude of the losses estimated on the basis of the detailed data. Considering the low level of observed variability of losses (8%), the readily available data extracted from the Eurostat Census Hub can be used to assess with acceptable accuracy the seismic risk for all European countries. However, the opinion of local experts on the distribution of the set of buildings in the different vulnerability classes is of great importance in such studies.

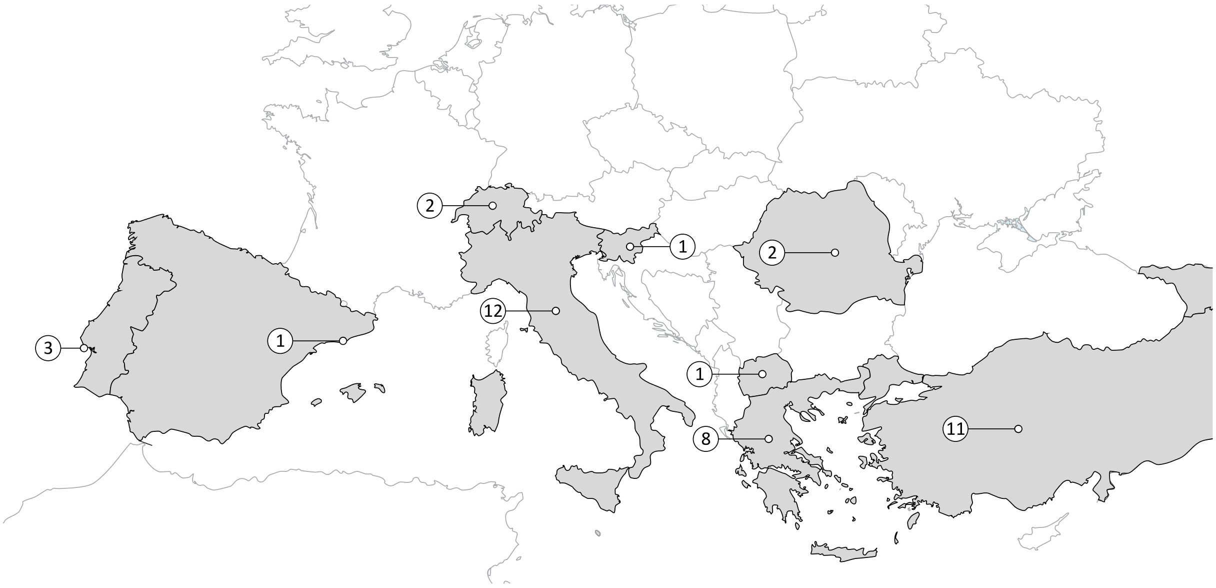
Figure 6. Normalized losses based on detailed national data (left) and European data (right) (Sousa et al 2017)



4 Modelling the vulnerability of the European building stock

An effort was made to collect the fragility curves that are available in the technical literature for reinforced concrete and masonry buildings in Europe and to perform a qualitative assessment, in order to assist in the selection of the most appropriate ones for a given geographical area and building typology (Maio et al 2017). 39 sets of fragility curves were collected from the literature, reviewed with focus on their most important features and assessed according to a series of qualitative criteria. The reviewed fragility curves were developed for the building stock of the countries shown in Figure 7, which are characterised by medium or high seismicity.

Figure 7. Number of existing fragility curves by country (Maio et al 2017)



The assessment criteria were based on the work of Rossetto et al (2014), which aimed to provide guidance to produce combined mean fragility curves. The following fundamental aspects were examined:

— capacity: structural characteristics, model used to compute the capacity and numerical model used for the response analysis;

— demand: ground motion to which the structure is subject and its variability;

— methodology for fragility analysis: sample size, definition of damage states and intensity measures;

— uncertainty in capacity (mechanical properties, geometric parameters, structural detailing and numerical modelling), demand (variability of the ground motion characteristics) and definition of damage state thresholds.

Low (L), medium (M) or high (H) rating was assigned to each set of fragility curve according to each qualitative evaluation criterion, as shown in Table 1. Among all the examined fragility curves, a high rating was assigned to the treatment of uncertainty in capacity and in seismic demand and to the use of site-specific seismic input. On the other hand, most fragility curves were assigned a low rating with respect to the use of non-structural components in the analysis and to the consideration of shear failure of members and of geometric irregularities.

Table 1. Qualitative assessment criteria and rating of numerical fragility curves for reinforced concrete and masonry buildings (Maio et al 2017)

Category	Evaluation criteria	Rating		
		Low (L)	**Medium (M)**	**High (H)**
Capacity	Non-structural elements (in RC buildings)	No	-	Yes
	Number of classes of building height	1	2, 3	> 3
	Analysis type	NLS-SMM	NLS	NLD
	Model type	SDoF	Reduced MDoF	MDoF
	Shear failure (RC buildings)	No	-	Yes
	Out-of-plane mechanism (URM buildings)	No	-	Yes
	Horizontal diaphragms (URM buildings)	No	-	Yes
	Geometric irregularities	No	-	Yes
Demand	Seismic demand	Code-based spectra	< 7 accelerograms	≥ 7 accelerograms
	Site-specific	No	-	Yes
Methodology	Damage state thresholds definition	Pre-set	-	Custom
	Intensity measure	1	2, 3	> 3
	Sample size	One building	Few buildings	Several buildings
Uncertainty	Capacity	No	-	Yes
	Seismic demand	No	-	Yes
	Damage state thresholds	No	-	Yes

NLS-SMM: non-linear static analysis with simplified mechanical models
NLS: non-linear static analysis
NLD: non-linear dynamic analysis
SDoF: single-degree-of-freedom
MDoF: multi-degree-of-freedom

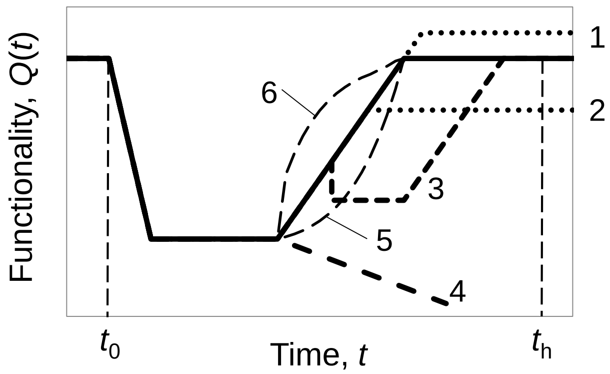
5 Modelling the resilience of the built environment

5.1 Definition and quantification of resilience

Resilience introduces the time dimension to consider the post-event recovery phase and extends the scope beyond the single structure, to systems and communities. The United Nations Office for Disaster Risk Reduction defines resilience as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure (UNISDR 2005). Focusing on earthquake engineering, the Multidisciplinary Center for Earthquake Engineering Research defines resilience as the ability of a system to reduce the chances of a shock, to absorb a shock if it occurs and to recover quickly afterwards (Bruneau et al 2003). More specifically, a resilient system shows i) reduced failure probabilities; ii) reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences; and iii) reduced time to recovery.

Figure 8 shows that, following a disruptive event at t_0, the functionality of the system will remain at its residual value for the time necessary to mobilise resources and plan the required interventions. It will then start to increase as the planned measures will be implemented. It might be decided to reach a higher or lower level of functionality compared to the initial one; these options are shown respectively by the dotted lines numbered 1 and 2. The dashed line 3 illustrates the case of a subsequent event that occurs during the recovery period. Finally, line 4 corresponds to the case that no action is taken to restore the functionality and the asset is left to degrade. For simplicity, a linear recovery path is often assumed, but other paths are possible, as indicated by lines 5 and 6.

Figure 8. Functionality versus time for different target functionalities and recovery paths



Among several mathematical expressions that have been proposed for resilience, R, the most popular is the one that calculates the area below the functionality curve from t_0, when the event occurs, until t_h, i.e. a sufficiently large period of time after full recovery:

$$R = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} Q(t)\,\mathrm{d}t \, .$$

In the technical literature, several metrics have been proposed for the functionality of lifelines, transportation networks, bridges, hospitals, economy, society, environment, and governmental services. Nevertheless, there is lack of consensus on the most representative one, both among different stakeholders, e.g. engineers, practitioners and inter-disciplinary researchers, and as regards the specific asset, e.g. society, economy, infrastructure, etc. Multi-dimensional metrics for functionality have also been proposed, e.g. Cutter et al (2010), Arcidiacono et al (2012), Renschler et al (2010). They are essentially a weighted sum of performance metrics for different assets, possibly considering the correlation among them and used in non-dimensional form to ease comparisons. Weights are currently based on expert opinion.

5.2 Post-event recovery of the built environment

Modelling the recovery process after a disruptive event is an essential issue in resilience assessment of the built environment. HAZUS (FEMA 2013) provides restoration functions for lifelines (highways, railways, ports, airports, systems for distribution of water, oil, natural gas, and electricity, etc.) and their components and for essential facilities (e.g. emergency response centres, fire and police stations, hospitals, schools and universities). Real data have been collected on the restoration of lifelines after natural disasters. Examples include i) the distribution network for gas, electric power and water in the city of Sendai in Japan (Isumi et al 1985), ii) the electricity network in Carolina and Virginia for hurricane and ice storm hazards (Liu et al 2007), iii) the highway network, population, business and economy after the Kobe earthquake (Chang and Nojima 2001), and iv) the community, electric power and telecommunications network following hurricane Katrina (Reed et al 2009).

The curve shown in Figure 8 is characterised by uncertainty in the values of functionality and time corresponding to all the characteristic points. A simple way to account for uncertainty in the initial loss of functionality is through the use of fragility functions that provide the probability that a component will reach a specific damage state, conditional on the intensity of the hazard. The recovery time is a random variable with high uncertainties, depending on the hazard intensity and the availability of human, economic and material resources. In the absence of validated models for the restoration of buildings, different options for the recovery path may be assumed and then assessed following a probabilistic method with Monte-Carlo simulation (Barberis et al 2015). Alternatively, a decision tree may be used (Decò et al 2013): it contains the post-event damage states of the asset as the first branches and, for each of them, four branches corresponding to fast, average and slow recovery, and no action. A Monte Carlo analysis with appropriate distributions for the random variables (idle time, recovery time and immediate post-event functionality) yields the mean value and standard deviation of resilience, *R*, rapidity of recovery and total cost.

Recent efforts have concentrated on advancing technical aspects for the practical implementation of resilience in the built environment, such as using event trees to combine the physical damage to buildings with the homeowners' decisions regarding reconstruction or relocation in order to simulate the recovery of housing after an earthquake (Burton and Kang 2017). Modelling urban areas as networks of buildings (residential and schools), allows to combine the social and physical functionality and consequently to assess the resilience of cities (Bozza et al 2017). Furthermore, Wade et al (2017) report on the design of the new Long Beach City Hall Building for functional recovery within 30 days, re-occupancy within 7 days, and less than 5 % loss relative to the building replacement value for the design earthquake. The final design was selected through iterations of loss analyses.

6 Concluding remarks and future work

A homogeneous database of the building stock in 30 European countries (the 28 Member States of the European Union plus Norway and Switzerland) was developed from data collected from the Eurostat Census Hub, namely the number of dwellings by period of construction of the building and population. The dwellings were classified in three classes of seismic vulnerability, based on the seismic design code in force in each country at the time of the building construction.

In the seismic-prone regions of Europe, the majority of buildings was designed without provisions for earthquake resistance or with moderate-level seismic codes. They are therefore vulnerable to earthquakes, may have a significant impact on a high percentage of the population and are in need of interventions that will reduce their vulnerability and consequently the risk of socio-economic losses.

Fragility curves are a necessary tool for the seismic risk assessment, establishing the link between the seismic hazard at a site and its effects on the built environment. The review of fragility curves available in the technical literature and the assessment of the most significant features according to a set of qualitative criteria provided an insight on the literature and serves to support the selection of the most appropriate fragility curves for a given geographic area and structural typology of the European building stock.

Models for the recovery of the built environment after a seismic event are still at an early development phase. Indeed, while there is a wealth of data on the observed damage after an earthquake (which serves for modelling the vulnerability) there is a lack of data on the progress of the post-earthquake reconstruction. Such data would require a significant and coordinated effort to collect and should associate the state of the physical assets to the capacity (technical, economic, organisational etc.) of the community.

The data and models described previously may be used as input for estimating the expected physical damage and associated losses in the European building stock, the necessary recovery time and cost, and the population exposed to the impact of earthquakes. The simplest case will consider a single scenario, for instance the design action described in the national codes for the seismic design of buildings. More complex hazard models are necessary for a full probabilistic assessment. The results of the risk assessment will serve for the identification of the areas that are at higher risk and for the definition of measures aiming at the prevention of risk. The impact assessment may be repeated for the alternative intervention strategies in order to assess their effectiveness.

This work may be complemented by the assessment of the resilience of the built environment in Europe (in terms of recovery time) for the current conditions and for the different intervention scenarios. Given the scarcity of models, such assessment may only be considered indicative.

In a broader context, the data and models are useful for emergency response and planning, and for supporting decision-making on building renovation. Furthermore, the database of buildings may also be used for risk studies regarding other natural hazards that may impact the built environment and for the assessment of the energy efficiency of buildings.

References

Arcidiacono V, Cimellaro GP, Reinhorn AM, Bruneau M (2012). Community resilience evaluation including interdependencies. Proceedings of the 15th World Conference on Earthquake Engineering, 24-28 September, Lisbon, Portugal.

Barberis F, Malavisi M, Cimellaro GP, Mahin S (2015). Fragility curves of restoration processes for resilience analysis. Proceedings of the 12th International Conference on Applications of Statistics and Probability in Civil Engineering, 12-15 July, Vancouver, Canada.

Bozza A, Napolitano R, Asprone D, Parisi F, Manfredi G (2017). Alternative resilience measures for urban systems subjected to seismic and landslide hazards. 16th World Conference on Earthquake Engineering, Santiago, Chile

Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, Shinozuka M, Tierney K, Wallace WA, von Winterfeldt D (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra, 19(4): 733-752.

Burton H, Kang H (2017). Towards the seismic resilience of residential communities: a conceptual framework and case study. Proceedings of the 16th World Conference on Earthquake Engineering, 9-13 January, Santiago, Chile.

CEN (2004). Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings. European Committee for Standardization, Brussels.

Coburn AW, Spence R (2002). Earthquake protection. Wiley, UK.

Chang SE, Nojima N (2001). Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective. Transportation Research Part A: Policy and Practice, 35(6): 475-494.

Crowley H, Özcebe S, Spence R, Foulser-Piggott R, Erdik M, Alten K (2012). Development of a European building inventory database. Proceedings of the 15th World Conference on Earthquake Engineering, 24-28 September, Lisbon, Portugal.

Cutter SL, Burton CG, Emrich CT (2010). Disaster resilience indicators for benchmarking baseline conditions. Journal of Homeland Security and Emergency Management 7(1): 1547-7355.

Decò A, Bocchini P, Frangopol DM (2013). A probabilistic approach for the prediction of seismic resilience of bridges. Earthquake Engineering and Structural Dynamics, 42(10): 1469-1487.

Eurostat (2015). Regions in the European Union – Nomenclature of territorial units for statistics NUTS 2013/EU-28. Publications Office of the European Union, Luxembourg.

FEMA (2008). HAZUS99 MH Estimated annualized earthquake losses for the United States. FEMA 366, Federal Emergency Management Agency Mitigation, Washington DC, USA.

FEMA (2013). Hazus®–MH 2.1, Earthquake model technical manual. Federal Emergency Management Agency, Washington DC, USA.

Gamba P (2014). Global Exposure Database: scientific features. GEM Technical Report 2014-10, GEM Foundation, Pavia, Italy.

Giardini D, Woessner J, Danciu L, Crowley H, Cotton F, Grünthal G, Pinho R, Valensise G, the SHARE consortium (2013). SHARE European Seismic Hazard Map for Peak Ground Acceleration, 10% Exceedance Probabilities in 50 years, doi: 10.2777/30345, ISBN-13, 978-92-79-25148-1.

Gioncu V, Mazzolani F (2001). Earthquake engineering for structural design. Spon Press, ISBN 0-203- 84889-6.

Jaiswal K, Wald D, Porter K (2010). A global building inventory for earthquake loss estimation and risk management. Earthquake Spectra, 26(3): 731-748.

Isumi M, Nomura N, Shibuya T (1985). Simulation of post-earthquake restoration for lifeline systems. International Journal of Mass Emergencies and Disasters, 3(1): 87-105.

Liu H, Davidson RA, Apanasovich TV (2007). Statistical forecasting of electric power restoration times in hurricanes and ice storms. IEEE Transactions on Power Systems, 22(4): 2270-2279.

Maio R, Tsionis G, Sousa ML, Dimova S (2017). Review of fragility curves for seismic risk assessment of buildings in Europe. Proceedings of the 16th World Conference on Earthquake Engineering, 9-13 January, Santiago, Chile.

Palermo V, Tsionis G, Sousa ML (2018). Building stock inventory to assess seismic vulnerability across Europe. Proceedings of the 16th European Conference on Earthquake Engineering, 18-21 June, Thessaloniki, Greece.

Reed DA, Kapur KC, Christie RD (2009). Methodology for assessing the resilience of networked infrastructure. Systems Journal, 3(2): 174-180.

Renschler CS, Fraizer AE, Arendt LA, Cimellaro GP, Reinhorn AM, Bruneau M (2010). A framework for defining and measuring resilience at the community scale: The PEOPLES resilience framework. National Institute for Standards and Technology.

Rossetto T, D'Ayala D, Ioannou I, Meslem A (2014). Evaluation of existing fragility curves. In: SYNER-G: Typology definition and fragility functions for physical elements at seismic risk, Ch. 3, Springer.

Silva V, Crowley H, Varum H, Pinho R, Sousa L (2015a). Investigation of the characteristics of Portuguese regular moment-frame RC buildings and development of a vulnerability model. Bulletin of Earthquake Engineering, 13(5), 1455-1490.

Silva V,·Crowley H, Varum H, Pinho R (2015b). Seismic risk assessment for mainland Portugal. Bulletin of Earthquake Engineering, 13(2), 429-457.

Sousa ML, Tsionis G, Dimova S (2017). Effect of the detail of exposure data in large-scale seismic risk assessment. Proceedings of the 16th World Conference on Earthquake Engineering, 9-13 January, Santiago, Chile.

Spence R, Foulser-Piggott R, Pomonis A, Crowley H, Guéguen P, Masi A, Chiauzzi L, Zuccaro G, Cacace F, Zulfikar C, Markus M, Schaefer D, Sousa ML, Kappos A (2012). The European building stock inventory: creating and validating a uniform database for earthquake risk modelling and validating a uniform database for earthquake risk modelling risk modelling. Proceedings of the 15th World Conference on Earthquake Engineering, 24-28 September, Lisbon, Portugal.

Tsionis G (2015). European building inventory framework. Report EUR 27603 EN, Publications Office of the European Union, Luxembourg.

UNISDR (2005). Hyogo framework for action 2005-2015: Building the resilience of nations and communities to disasters. United Nations Inter-Agency Secretariat of the International Strategy for Disaster Reduction, Geneva.

UNISDR (2015) The Sendai framework for disaster risk reduction 2015-2030. The United National Office for Disaster Risk Reduction

Wade K, Cook D, Haselton C (2017). New developments in resilience-based seismic design and enhanced building-specific risk assessment in the U.S. Proceedings of the 16th World Conference on Earthquake Engineering, 9-13 January, Santiago, Chile.

Woessner J, Laurentiu D, Giardini D, Crowley H, Cotton F, Grünthal G, Valensise G, Arvidsson R, Basili R, Demircioglu MB, Hiemer S, Meletti C, Musson RW, Rovida AN, Sesetyan K, Stucchi M, the SHARE Consortium (2015). The 2013 European seismic hazard model: key components and results. Bulletin of Earthquake Engineering, 13(12): 3553-3596.

List of figures

List of tables

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: http://europea.eu/contact

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

- at the following standard number: +32 22999696, or

- by electronic mail via: http://europa.eu/contact

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: http://europa.eu

EU publications

You can download or order free and priced EU publications from EU Bookshop at: http://bookshop.europa.eu. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see http://europa.eu/contact).

KJ-NA-29053-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2760/923762
ISBN 978-92-79-77703-5