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Model of Seismic Design Lateral Force Levels for the Existing Reinforced Concrete European Building Stock

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Abstract

As part of the development of a European Seismic Risk Model 2020 (ESRM20), the spatial and temporal evolution of seismic design across Europe has been studied in order to better classify reinforced concrete buildings (which represent more than 30% of the approximately 145 million residential, commercial and industrial buildings in Europe) and map them to vulnerability models based on simulated seismic design. This paper summarises the model that has been developed to assign the years when different seismic design levels (low code, moderate code and high code) were introduced in a number of European countries and the associated lateral forces that were specified spatially within each country for the low and moderate codes for typical reinforced concrete mid-rise buildings. This process has led to an improved understanding of how design regulations evolved across Europe and how this has impacted the vulnerability of the European residential building stock. The model estimates that ~60% of the reinforced concrete buildings in Europe have been seismically designed, and of those buildings ~60% have been designed to low code, ~25% to moderate code and 15% to high code. This seismic design model aims at being a dynamic source of information that will be continuously updated with additional feedback from local experts and datasets. To this end, all of the data has been made openly available as shapefiles on a GitLab repository.

Keywords: *seismic design evolution, lateral force levels, European building stock, exposure model, seismic zonation maps, seismic risk*

Introduction

The practice of seismic design and zonation in Europe and across the World has been covered in various reference papers/reports (e.g. Mayordomo et al. 2004; Doğangün and Livaoğlu 2006; Solomos et al., 2008, fib Bulletin-69, 2013; Daniell, 2015), handbooks (e.g. Paz, 1994), international initiatives (e.g. the information network of earthquake disaster prevention technologies of the IISEE[1], the IAEE's 'Regulations for Seismic Design – A World list'[2]), international conferences (e.g. Sixth International Conference on Seismic Zonation[3]) and

[1] https://iisee.kenken.go.jp/net/?mod=code
[2] http://www.iaee.or.jp/worldlist.html
[3] https://www.eeri.org/products-page/international-conference-on-seismic-zonation/6th-international-conference-on-seismic-zonation-2/

European projects (e.g. RISK-UE, see Milutinovic and Trendafiloski, 2003). The focus of most of these publications has been mainly to document the state of recent practice of seismic design and zonation, to enable a comparison between countries. Whilst such initiatives are important for the future development, improvement and harmonisation of seismic design codes, it should be considered that a significant proportion of the reinforced concrete building stock in Europe has been constructed before the introduction of these modern codes and thus an understanding of the evolution of seismic design is essential for the seismic risk assessment of European buildings.

Fajfar (2018) published an important summary of the changes in the analysis of structures over the past 100 years for the purposes of seismic design and assessment. As discussed in Fajfar (2018), up until 1978 the seismic design of buildings was dominated by the use of equivalent static procedures through the specification of a lateral force coefficient (or seismic coefficient), and this practice is still widely used today for simple regular structures, with updated values for the lateral force coefficients. Over the years, updates to the method of calculation of the lateral force coefficients have accounted for the dynamics of the structures, as well as material ductility, and concepts of randomness (safety factors) have been introduced in the design calculations (Fajfar, 2018).

As part of the RISK-UE project, the design lateral force coefficients as a function of fundamental period were estimated for reinforced concrete frame buildings in two time periods (1966 and in 1992) for Spain, France, Italy, North Macedonia, Greece, Romania and Bulgaria. Building upon this study initiated in RISK-UE, this paper summarises the spatial and temporal model that has been developed to distinguish between reinforced concrete buildings in Europe according to the key principles of seismic design and the levels of lateral forces to which these buildings were designed. An understanding of the level of design of a given building class is fundamental for the development of vulnerability models that are capable of representing the features of each design level (see e.g. Borzi et al., 2008; Verderame et al., 2010; Romão et al., 2019). Furthermore, a comparison of design capacity maps with the latest seismic hazard maps provides a good indicator of seismic safety and has been used in prioritisation schemes for retrofitting of school buildings (see e.g. Grant et al., 2007).

The study presented herein has contributed to the development of a European exposure model (Crowley et al., 2020a), a component of the European Seismic Risk Model (ESRM20) (Crowley et al., 2019) which is being released through the risk services of EFEHR, the European Facilities for Earthquake Hazard and Risk (https://eu-risk.eucentre.it).

Simplified Categories of European Design Codes

For a harmonised classification of seismic design codes across Europe, the following four simple categories of seismic design (described in more detail subsequently) have been identified:

- CDN: no seismic design
- CDL: low code (i.e. the first generation of seismic design codes)

- CDM: moderate code (i.e. the second generation of seismic design codes)
- CDH: high code (i.e. the latest generation of seismic design codes)

Buildings of design class CDN were typically designed to older codes (from before the 1960's) that used allowable stresses and very low material strength values and considered predominantly the gravity loads. Buildings of design class CDL were designed considering the seismic action by enforcing values of the seismic coefficient, β (referred to herein as lateral force coefficient). Structural design for these codes was typically based on material-specific standards that used allowable stress design or a stress-block approach.

Seismic design including modern concepts of ultimate capacity and partial safety factors (limit state design) and/or with better detailing to improve global ductility, was the basis of the CDM category of codes. The seismic action was also accounted for in the design by enforcing values for the lateral force coefficient, β. It is noted that the distinction between CDL and CDM codes is not always straightforward and varying interpretations from those presented later in this study could be made by different engineers. Finally, the CDH class refers to modern seismic design principles that account for capacity design and local ductility measures, similar to those available in Eurocode 8 (CEN, 2004) for ductility class medium (DCM) (which is assumed to reflect the most frequently adopted ductility class).

An important issue worth mentioning here is the consideration of the quality of code enforcement and compliance. This effect within the building stock of a given construction period is assumed to be random, and it is thus not explicitly reported in the exposure model but is instead considered within the building-to-building variability of the vulnerability models (Romão et al., 2019). The vulnerability models for reinforced concrete buildings in the European Seismic Risk Model are based on simulated design, considering each of the aforementioned design classes (CDL, CDM and CDH). Numerical models of the designed buildings are developed and capacity curves are obtained through nonlinear static analysis (these capacity curves are openly available from the following online resource: Romão et al., 2020). In order to account for code enforcement and compliance, the design values of stirrup spacing, concrete cover, concrete strength, and steel yield strength of the longitudinal and transverse reinforcement are modified for implementation in the numerical models through quality factors (which have three levels: good, moderate, bad). Currently, a Europe-wide assumption on these quality factors for each design code (CDL, CDM and CDH) has been made when developing the vulnerability models, but these quality factors could be varied in the future for each country as a function of the percentage of buildings deemed to have good, moderate and bad enforcement/compliance in each construction period.

The years when each of these design classes were introduced in European countries with a history of seismic design are summarised in Table 1, and presented in Figure 1. This table provides the first year when a given class of design code was introduced, but also provides in some cases the years when important updates to the seismic zonation maps were made, which led to a modification to the lateral force specified in the design. The seismic zonation maps identified the areas where the code had to be applied within the country and in many cases only limited areas of the country needed to apply the first set of seismic regulations and these areas grew over time, as described in the next section.

Table 1. Years when major changes to the code level and/or associated seismic zonation were made in each country (and commonly used acronyms for the codes, where appropriate – see Appendix for full details of the codes). The years in bold font correspond to the codes that have been considered so far in the European exposure model.

Country	Low Code	Moderate Code	High Code	Additional References
Albania	1952 1963 **1978** (KTP 2-78)	**1989** (KTP-N.2-89)	-	Bilgin and Korini (2013), Babellëkuu and Myftaraga (2020), Freddi et al. (2021)
Austria	1955 (ÖNORM B 4000-3) **1979** (ÖNORM B 4015-1)	-	1997 (ÖNORM B 4015-1) 1999 (ÖNORM B 4015-2) 2002, **2006** (ÖNORM B 4015) 2009 (EC8)	Adam (2012)
Bulgaria	1947 (NSDC-47) **1957** (NSDC-57) 1961 (NSDC-61) **1964** (NSDC-64)	**1987** (NSDC-87)	2012 (EC8)	Dimova et al. (2015)
Cyprus	-	**1992**	2011 (EC8)	Loyides (1993), Paris (2012), Dimova et al. (2015)
France	**1969** (PS-69)	**1991** (AFPS-90)	2011 (EC8)	Jalil (1992), Boissonnade (1994), Dimova et al. (2015)
Germany	**1957** (DIN 4149)	**1981** (DIN 4149)	**2005** (DIN 4149)	
Greece	**1959**	**1984**	**1995** (NEAK-95)	Manos (1994)
Hungary	**1978** (MI-04 133-78)	-	**2006** (EC8)	Vertes (1994), Kegyes and

Country	Low Code	Moderate Code	High Code	Additional References
				Kegyes-Brassai (2007), Gobesz and Kegyes (2013)
Iceland	**1958**	**1976** **1989** (ÍST 13)	**2002** (EC8)	Tryggvason et al. (1958), Solnes et al. (2013)
Italy	**1915,** **1935,** **1984**	**1996**[1] (DM96)	2010 (NTC 2008)	Di Pasquale et al. (1999a, 1999b)
Portugal	**1958** (RSCCS) 1961 (RSEP) 1967 (REBA)	**1983** (RSAEEP/REBAP)	2010 (NP-EC8)	Costa et al. (2008), Proença and Gago (2011)
Romania	**1963** [2] (PI13-63) 1970 (P13-70)	**1978** (P100-78) 1981 (P100-81) 1991 (P100-91) **1992** (P100-92)	**2006** (P100-1/2006) 2013 (P100-1/2013)	MLPDA (2020), Craifaleanu et al. (2010)
Spain	**1962** (MV101, PGS 1) **1974** (PDS 1)	**1994** (NCSE-94)	**2002** (NCSR-02)	Diez and Larrea (2012), Barbat and Paz (1994)
Switzerland	**1970** (SIA 160)	**1989** (SIA 160)	**2003** (SIA 261)	Wenk (2015), Lestuzzi (2012)
Turkey	1944 1949 1953 1968 **1975**	-	**1997**	Soyluk and Harmankaya (2012), Durgunoglu (1994)
Former Yugoslavia [3]	1948 **1964**	**1981**	>2006	Jurukovski and Gavrilovic (1994)

[1] This code has been assigned CDM even though allowable stress design was still possible (and was commonly adopted) due to the improved detailing to improve local and global ductility

[2] After the 1940 Vrancea earthquake, seismic building design instructions (not compulsory) were published in 1941 and 1945, however with limited effects in practice. In 1952 a seismic zonation standard was published (STAS 2923-52), but seismic design code provisions drafted in 1956 or 1958 failed to be adopted.

[3] Includes: Bosnia and Herzegovina, Croatia, Kosovo, Montenegro, North Macedonia, Serbia, Slovenia

The values in bold in Table 1 represent the years that have been considered in the European exposure model; not all code changes have been considered given that the focus is at the European level. In some countries (e.g. Turkey, ex-Yugoslavian countries), the year that has been considered in the exposure model corresponds to that when the design class was widely enforced/implemented rather than the first year when the seismic design class was introduced. In general it should be considered the date of publication of a standard does not necessarily correspond to the date the building code was fully enforced, and this can be of particular relevance to the high code dates reported in Table 1. Indeed, the status of adoption of Eurocode 8 (CEN, 2004) in the former Yugoslavian countries is complex – for these countries only the years when EC8 was first formally enforced are shown for each country in Figure 1 (noting that in most cases EC8 has been introduced earlier, and in parallel with the 1981 ex-Yugoslavian code).

The commonly used acronyms of the codes are provided in Table 1, whereas the full references for the codes are given in the Appendix. This table has been compiled using the knowledge of the authors (which covers the majority of the countries in Table 1), access to the original code documentation, key references including IISEE[1] and Paz (1994), as well the additional references provided in the last column of Table 1.

There are around 145 million buildings in the European exposure model (Crowley et al., 2020a), and around 30% of these are modelled as reinforced concrete. Figure 2 shows the application of the temporal evolution of seismic design presented above to the European exposure model, and shows the number of reinforced concrete buildings and their distribution between the different seismic design code levels for each country in Europe. Of the reinforced concrete buildings, around 60% have some level of seismic design, with ~60% of those designed to low codes, ~25% to moderate codes and ~15% to high codes.

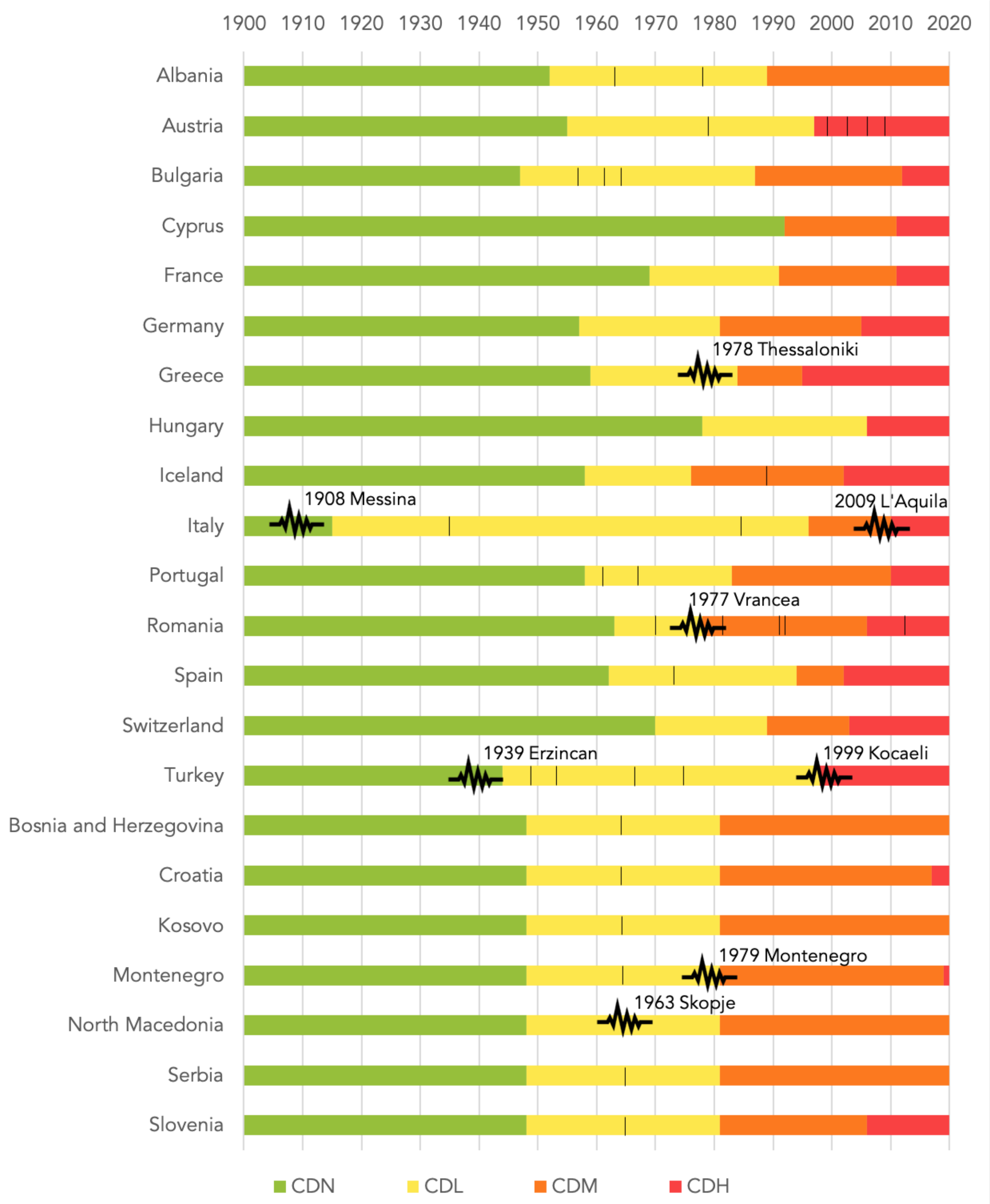


Figure 1. Temporal evolution of seismic design codes across European countries. Vertical black lines show when important changes within a category of design code were made. Some important earthquakes which have influenced seismic design in Europe are also shown.

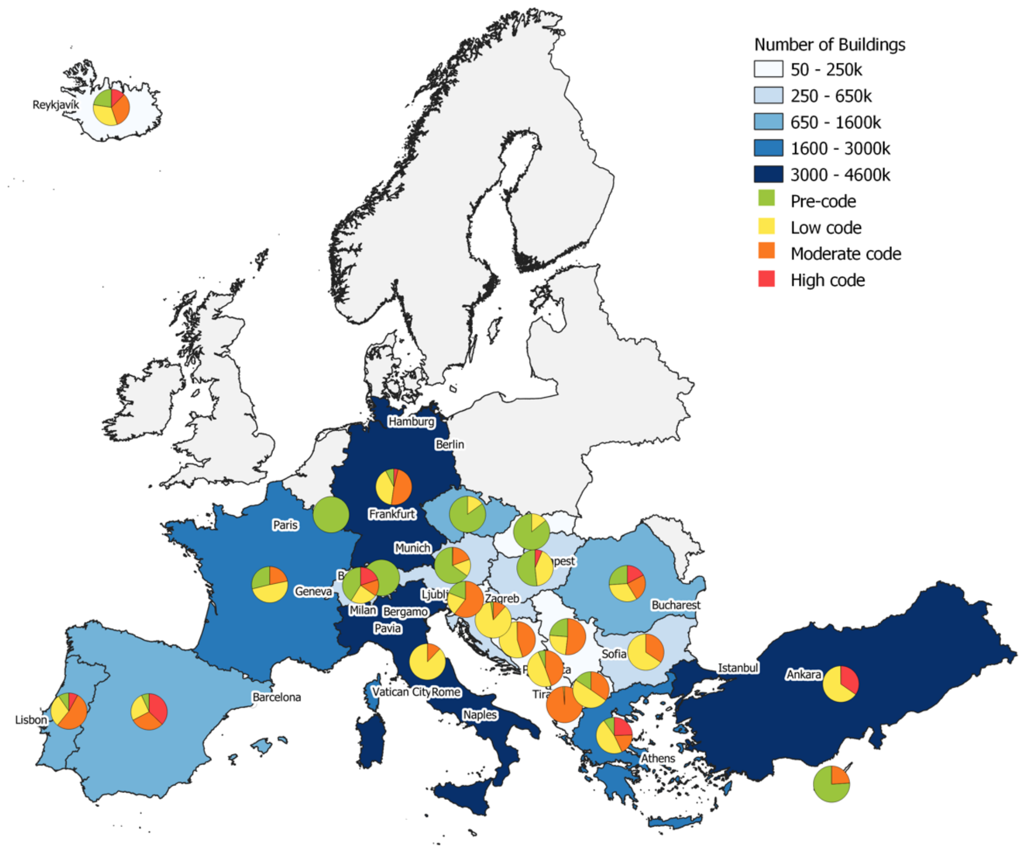


Figure 2. Map showing the number of reinforced concrete buildings in each country in the European exposure model with pie-charts showing the percentage that are pre-code (CDN), low code (CDL), moderate code (CDM) and high code (CDH)

Calculation of Lateral Force Coefficients

The design lateral force coefficient, β (i.e. the fraction of the weight of the building defining the lateral force) that was specified in each of the low and moderate design codes for typical mid-rise reinforced concrete frames has been calculated by retrieving the seismic zonation maps supplied with each design code and applying the specified coefficients in the following standard formula which has been found to be generally applicable to all of the design codes (with some small variations):

$$\beta = K_s \cdot K_o \cdot K_d \cdot K_p \qquad [1]$$

where K_s is a coefficient based on seismic intensity, K_o is a coefficient based on the type/importance of the building, K_d is a coefficient that accounts for dynamic response, and K_p is a coefficient that accounts for ductility and energy dissipation (and in modern codes also accounts for overstrength). In some codes the values of this last coefficient are provided as $1/K_p$ but they have been converted to K_p herein for the standard implementation of Equation (1). It is noted that in the older generation of codes, K_s is directly provided for different soil types and the dynamic coefficient is only a function of the building type, whereas in more recent codes the effect of the soil is either accounted for with an additional coefficient or is integrated into the dynamic coefficient (K_d). In some CDM codes (with limit state design), the lateral force coefficient is further multiplied by a partial safety factor for loads. This has not been included in Equation (1) as it appears to only be different from 1 for the Portuguese code.

Tables 2 and 3 present the values of each of the coefficients of Equation (1), that have been retrieved from the low and moderate codes in Table 1, and the calculation of the lateral force coefficient for each seismic intensity zone for a medium-rise residential building with a reinforced concrete (RC) frame structure on medium soil, with an assumed period of vibration of 0.5 s. It is noted that for Iceland the calculations have been made using RC wall buildings as there are very few RC frame buildings in the country, according to the exposure model proposed by Crowley et al. (2020a). Only a focus on the low (CDL) and moderate (CDM) codes has been made herein as they make up 85% of the seismically designed reinforced concrete buildings in Europe, and given that the building stock is being classified for loss assessment, buildings designed with no or low levels of seismic design will influence most the total losses. Interested readers are referred to other publications that have focused on comparing the seismic zonation in these modern codes (e.g. Solomos et al. 2008, Mayordomo et al. 2004). Nevertheless, future extensions of this study will include the calculation of the lateral force coefficients for the high codes given in Table 1, as the number of buildings designed to these modern codes continues to grow across Europe and to provide input to studies considering the impact of upgrading buildings to current code standards.

It is acknowledged that the lateral force coefficient for a mid-rise reinforced concrete building is a simplistic representation of the evolution of seismic design in Europe, and differences in, for example, seismic mass modelling, section detailing, and changes with period of vibration, have not been considered herein. Nevertheless, it is believed that such an approach is appropriate for a regional exposure model covering the whole of Europe, and will allow the relative vulnerability of reinforced concrete buildings across Europe to be adequately represented within the European Seismic Risk Model (ESRM20).

Table 2. Coefficients (K_s, K_o, K_d, K_p) used to calculate the lateral force coefficient (β) for the low codes (CDL) and the years for which they have been applied in the European exposure model. Note that only the code years reported in bold in Table 1 have been considered for simplicity of the exposure model.

Country	**From year**	**To year**	**Zone**	K_s	K_o	K_d	K_p	β
Albania	1978	1989	VII	0.025	-	1.8	-	0.045
			VIII	0.05				0.09
			IX	0.1				0.18
Austria	1979	2002	I	0.01	-	2.5	-	0.03
				0.02				0.05
				0.025				0.06
				0.03				0.08
				0.035				0.09
			2	0.04				0.10
				0.05				0.13
				0.06				0.15
			3	0.07				0.18

Country	From year	To year	Zone	K_s	K_o	K_d	K_p	β
			4	0.12				0.30
Bulgaria	1957	1964	VII VIII IX	0.025 0.05 0.1	-	-	-	0.025 0.05 0.1
	1964	1987	VII VIII IX	0.025 0.05 0.1	1.0[1]	1.8	1.0	0.045 0.09 0.18
France	1969	1991	Ia & Ib II III	0.5 1 1.5	-	0.082	-	0.04 0.08 0.12
Germany	1957	1981	I II	0.0375 0.075	-	-	-	0.0375 0.075
Greece	1959	1984	I II III	0.06 0.08 0.12	1.0	-	-	0.06 0.08 0.12
Hungary	1978	2006	6 7 8 9	0.15 0.22 0.26 0.32	1.0	2.15	0.25	0.08 0.14 0.16 0.20
Iceland	1958[2]	1976	-	0.07	-	-	-	0.07
Italy	1915	1935	II I	0.1 0.125	-	-	-	0.1 0.125
	1935	1984	II I	0.07 0.1	-	-	-	0.07 0.1
	1984	1996		0.04 0.07 0.1	-	-	-	0.04 0.07 0.1
Portugal	1958	1983	B A	0.05 0.1	-	-	-	0.05 0.1
Romania[3]	1963	1970	VII VIII IX	0.025 0.05 0.1	-	1.8	1.2	0.04 0.085 0.175
	1970	1978 [4]	VII VIII IX	0.03 0.05 0.09	-	1.6	1	0.04 0.065 0.1
Spain	1962	1974	VII VIII IX X	0.04 0.08 0.1 0.15	-	-	-	0.04 0.08 0.1 0.15
	1974	1994	V VI VII VIII IX	0.02 0.04 0.08 0.15 0.2	-	-	-	0.02 0.04 0.08 0.15 0.2

Country	From year	To year	Zone	K_s	K_o	K_d	K_p	β
Switzerland	1970	1989	-	0.02	-	-	-	0.02
Turkey	1975	1997	4 3 2 1	0.03 0.06 0.08 0.1	1.0	1.25	1.5	0.06 0.11 0.15 0.19
Former Yugoslavia[5]	1964	1981	VII VIII IX	0.025 0.05 0.1	-	1.5	-	0.0375 0.075 0.15

[1] For more important structures a shift in the seismic zone (from lower to higher) is made.

[2] In 1958 the first seismic hazard map was presented in Iceland (Tryggvason et al. 1958) and in the following years a design lateral force coefficient of 1/15 was common practice in the small engineering community in the island, despite not being officially required by building authorities nor given in building regulations or codes.

[3] The final value of β also considered a coefficient (eps) that took into account the equivalence between the real building and a simplified SDOF (assumed 0.8 for regular buildings); for highly important buildings, higher K_s values were specified.

[4] It is noted that the European exposure model does not currently include this change of lateral force coefficient from 1970 to 1978, but it is reported here so that it can be included in future updates.

[5] Includes: Croatia, Serbia, Slovenia, Bosnia and Herzegovina, Kosovo, North Macedonia and Montenegro.

Table 3. Coefficients (K_s, K_o, K_d, K_p) used to calculate lateral force coefficients (β) for the moderate codes (CDM) and the years for which they have been applied in the European exposure model. Note that only the code years reported in bold in Table 1 have been considered for simplicity of the exposure model.

Country	From year	To year	Zone	K_s	K_o	K_d	K_p	β
Albania	1989	2013	VII VIII IX	0.11 0.22 0.36	1.0	1.6	0.25	0.04 0.09 0.14
Bulgaria	1987	2012	VI VII VIII IX	0.05 0.1 0.15 0.27	1.0	2.4	0.3	0.04 0.07 0.11 0.19
Cyprus	1992	2011	I, II, III IV V	0.09 0.12 0.18	1.0	2	0.5	0.09 0.12 0.18
France	1991	2011	Ia Ib II III	0.10 0.15 0.25 0.36	-	2.15	0.2	0.04 0.07 0.11 0.15
Germany	1981	2005	1 2 3 4	0.013 0.024 0.046 0.08	-	0.92	-	0.01 0.02 0.04 0.07

Country	**From year**	**To year**	**Zone**	K_s	K_o	K_d	K_p	β
Greece	1984	1995	I II III	0.06 0.08 0.12	1.0	-	-	0.06 0.08 0.12
Iceland	1976	1989	I II III	0.25 0.5 1	-	0.1	1.33	0.03 0.07 0.13
	1989	2002	I II III IV	0.25 0.5 0.75 1	-	0.12	1.33	0.04 0.08 0.12 0.16
Italy	1996	2010	3 2 1	0.04 0.07 0.1	1.0	1.0	1.0	0.04 0.07 0.1
Portugal[1]	1983	2010	D C B A	0.3 0.5 0.7 1	-	0.28	0.4	0.03 0.06 0.08 0.11
Romania[2]	1978	1991	VI VI 1/2 VII VII 1/2 VIII VIII 1/2 IX	0.07 0.09 0.12 0.16 0.2 0.26 0.32	-	2	0.2	0.02 0.03 0.04 0.05 0.065 0.085 0.1
	1991	2006	F E D C B A	0.08 0.12 0.16 0.20 0.25 0.32	1.0	2.5	0.2	0.03 0.05 0.065 0.08 0.1 0.13
Spain	1994	2002	I II III	0.02 0.085 0.19	-	1.9	0.33	0.01 0.05 0.12
Switzerland	1989	2003	Z1 Z2 Z3a Z3b	0.06 0.1 0.13 0.16	0.67	2.1	0.4	0.03 0.06 0.07 0.09
Former Yugoslavia	1981	2005-2020	7 8 9	0.025 0.05 0.1	1.0	1.0	1.0	0.025 0.05 0.1

[1] As mentioned previously, these lateral force coefficients should be further multiplied by a partial safety factor equal to 1.5.

[2] The final value of β also considered a coefficient (eps) that took into account the equivalence between the real building and a simplified SDOF (assumed 0.8 for regular buildings).

As can be seen from Table 2, in many of the earliest seismic design codes introduced before the 1960's (e.g. in Italy, Bulgaria, Portugal) the lateral force coefficient was specified as a fixed value that was applied to areas where earthquakes had been observed in the past and it was thus just a function of the seismic intensity (which was often correlated with observed macroseismic intensity from past major earthquakes). The value of the lateral force coefficient was typically taken at around 10% with lower values in areas of the country where the observed effects of earthquakes had historically been less pronounced.

From the beginning of the 1960's, dynamic considerations were introduced in many codes by relating the lateral force coefficient to the natural period of vibration of the building (i.e. through a response spectrum) and later to the energy dissipation capacity of the structures (i.e. ductility and damping). As discussed in Chopra (2007), the idea to represent earthquake excitation by a response spectrum was first put forward in 1926 by K. Suyehiro, soon after the 1923 Tokyo earthquake. However, the widespread engineering use of response spectra did not take hold until the 1960's with the arrival of digital computing which made their calculation more reliable and less time consuming (Chopra, 2007; Trifunac, 2008). The first set of standard spectral shapes for design was developed by Housner (1959) by averaging and smoothing the response spectra from eight strong-motion records obtained from four earthquakes that occurred in the United States between 1934 and 1952. Trifunac (2008) describes the use of response spectra in design from the 1950's in the United States, whereby the dynamic response was accounted for using a coefficient (nominated K_d herein) that was inversely proportional to the period, which was also adopted in many European codes in the 1960's, as indicated in Table 4.

Table 4. Formulae used to calculate K_d in the low codes (CDL) considered in the exposure model (shown in bold in Table 1)

Country (Year)	Formulae to calculate K_d
Albania (1978)	$0.6 \leq K_d = 0.9/T \leq 3.0$
Austria (1979)	2.5 (maximum value)
Bulgaria (1964)	$0.6 \leq K_d = 0.9/T \leq 3.0$
France (1969)	$0.065/T^{1/3}$
Hungary (1978)	$2.5\left[\frac{T_0}{T}\right]^{2/3}$ where T_0 can be assumed = 0.4
Romania (1963)	$0.6 \leq K_d = 0.9/T \leq 3.0$ (for soil with bearing capacity ≥ 2 kg/cm^2)
Romania (1970)	$0.6 \leq Kd = 0.8/T \leq 2.0$ for normal soil condition
Turkey (1975)	$\frac{1}{(0.8\text{-}T\text{-}T_0)} \leq 1.0$ where T_0 is a function of site class
Former-Yugoslavia (1964)	$0.5 \leq 0.75/T \leq 1.5$

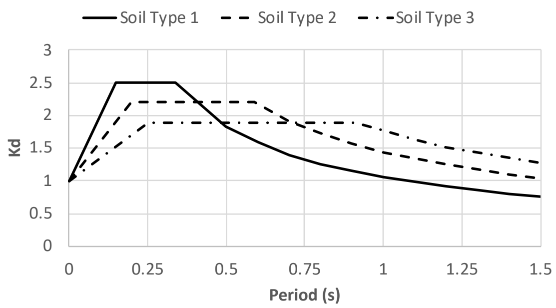
As discussed in Fajfar (2018), the first code to account for the energy dissipation capacity of structures in the inelastic range was the SEAOC model code in 1959. A coefficient (named K_p coefficient in Equation 1) was introduced to distinguish between the inherent ductility and energy dissipation capacities of different structures and varied between 1.33 for wall structures to 0.67 for moment frames. In 1963, the Romanian code introduced a coefficient (equal to 1.2) to account for the influence of friction damping in reinforced concrete moment resisting frames. The Bulgarian code of 1964 accounted for structural damping by specifying values between 0.5 and 1.5 as a function of the flexibility of the structure with 1.0 assumed herein for reinforced concrete frames with infill panels. The 1975 Turkish code specified a value of 1.5 for the 'structural coefficient' of nonductile moment-resisting frames with unreinforced masonry partition walls.

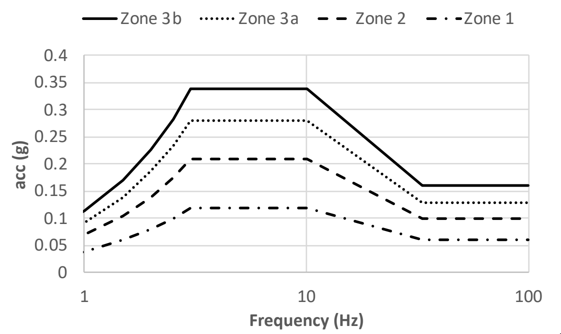
Over time, and following a number of large earthquakes, it became clear that the majority of well designed and constructed buildings survived strong ground motions, despite having only been designed for a fraction of the forces that would have developed had those structures behaved linearly elastically. By accounting for the energy dissipation and overstrength in the design, it became possible to reduce the seismic design forces. To account for this the 'response modification factor' was introduced in 1978 in the US within ATC 3-06 (Fajfar, 2018). Likewise, it can be seen from Table 2 that the 1978 Hungarian code specified a 'reduction factor' of 0.25 for reinforced concrete multistorey buildings without frame-shear wall interaction. It was explicitly stated that this factor accounted for the fact that the seismic forces were obtained from an elastic analysis and thus considered the effect of the potential nonlinear behaviour of the structure, ductility, internal force redistribution, and energy dissipation through damping. Table 2 shows, however, that there were still a number of countries in Europe that did not account for either the K_d or K_p coefficients in the calculation of the lateral force coefficients, even up until the 1990's (e.g. Italy, Spain, Greece).

Table 3 shows that the majority of the moderate codes were introduced in the 1980's and 90's and by then most codes included all of the coefficients in Equation (1). The formula to calculate the dynamic coefficient K_d in each moderate code is presented in Table 5. These design values show there was still divergence in the engineering community regarding the modelling of dynamic amplification in the code. Nevertheless, in many countries the trend was moving towards representing the seismic intensity coefficient with the peak ground acceleration in terms of g and amplifying the spectrum up to a maximum of 2.5 with different shapes as a function of the soil category.

Table 5. Formulae used to calculate K_d in the moderate codes (CDM) considered in the exposure model (shown in bold in Table 1)

Country	Formulae to calculate K_d
Albania (1989)	$0.65 \leq K_d = \frac{0.7}{T} \leq 2.3$ (soil category I) $0.65 \leq K_d = \frac{0.8}{T} \leq 2.0$ (soil category II) $0.65 \leq K_d = \frac{1.1}{T} \leq 1.7$ (soil category III)
Bulgaria (1987)	$0.8 \leq K_d = \frac{0.9}{T} \leq 2.5$ (soil category I) $0.8 \leq K_d = \frac{1.2}{T} \leq 2.5$ (soil category II) $1.0 \leq K_d = \frac{1.6}{T} \leq 2.5$ (soil category III)

Cyprus (1992)	2.5 for $T \leq 0.4$ s $2.5\left[\frac{0.4}{T}\right]$ for T > 0.4 s
France (1991)	for stiff soils: 2.5 for $T \leq 0.4$ s $2.5\left[\frac{0.4}{T}\right]^{2/3}$ $2.5\left[\frac{0.4}{3.2}\right]^{2/3}\left[\frac{3.2}{T}\right]^{5/3}$ (other periods and coefficients specified for other soil conditions)
Germany (1981)	1.0 for $T \leq 0.45$ s $0.528/T^{0.8}$ for T > 0.45 s (note that the seismic intensity coefficients in Table 3 are not PGA but corresponded to the maximum amplified coefficients)
Iceland (1976)	$0.05/\sqrt[3]{T} < 0.1$ 0.1 (for 1-2 storey buildings)
Iceland (1989)	$\frac{1}{15\sqrt{T}} < 0.12$ 0.12 (for 1-2 storey buildings)
Italy (1996)	1.0 for $T \leq 0.8$ s $0.862\left[\frac{1.0}{T}\right]^{2/3}$ for T > 0.8 s
Portugal (1983)	for soil category II: $\frac{0.2}{\sqrt{T}}, 0.25 \leq T \leq 2$ $0.4, T \leq 0.25$ (other periods and coefficients specified for other soil conditions)
Romania (1978)	$0.75 \leq K_d = 3/T \leq 2.0$ (for normal soil conditions)
Romania (1991, 1992)	2.5 for $T \leq T_C$ $2.5-(T-T_C)$ for $T > T_C$ (where the corner period (T_C) was given as 0.7 s, 1.0 s or 1.5 s as a function of the seismic condition of the zone)
Spain (1994)	

<table>
<tr><td>Switzerland (1989)</td><td>
</td></tr>
<tr><td>Former Yugoslavia (1981)</td><td>$0.5/T$, 0.33 $\leq K_d$ <1.0 (soil category I)
$0.7/T$, 0.47 $\leq K_d$ <1.0 (soil category II)
$0.9/T$, 0.60 $\leq K_d$ <1.0 (soil category III)</td></tr>
</table>

A comparison of the K_p coefficients in the moderate codes (Table 3) shows that all codes moved towards a 'reduction factor' approach with values between 0.1 and 0.5 for reinforced concrete frames, except in the former Yugoslavia where the value was fixed at 1.0. It is noted that when the importance coefficient was accounted for, it was found to be equal to 1.0 for ordinary residential buildings in all of the codes studied herein.

Application of Lateral Force Coefficients to the European Exposure Model

Maps of all of the seismic zones presented in Tables 2 and 3 have been obtained and geocoded in order to map the variation of the lateral force coefficients across Europe over the past century. The resulting shapefiles for each country have been made available on a GitLab repository[4]. Figure 3 has been produced using these shapefiles to show the spatial and temporal evolution of lateral force coefficients (as calculated above) across Europe from 1910 to 2000. This figure highlights that the biggest change in seismic design occurred in the 1970's when a large number of countries implemented seismic design codes, and the lateral force coefficients did not change significantly in most countries from then until the end of the last century. It should be noted, however, that this figure does not account for the change in code type from low to moderate, which will have led to improvements in the design over this period.

[4] https://gitlab.seismo.ethz.ch/efehr/esrm20_exposure/-/tree/master/seismic_design_shapefiles

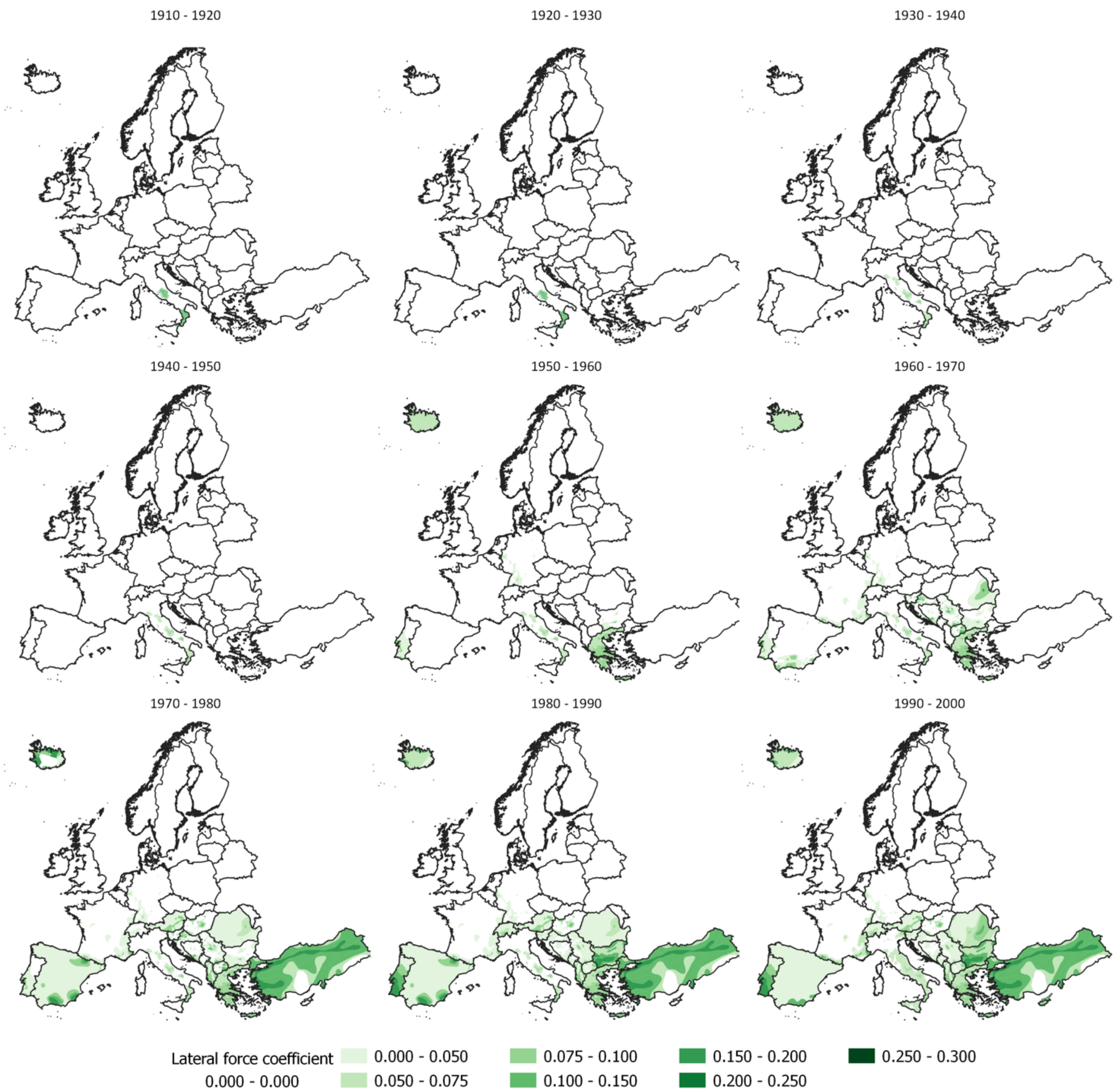


Figure 3. Spatial and temporal evolution of lateral force coefficients across Europe from 1910 to 2000. These maps can also be viewed through the following interactive viewer: https://maps.eu-risk.eucentre.it/map/european-seismic-design-levels (Crowley et al., 2020b)

These shapefiles have also been used to assign the lateral force coefficients to the reinforced concrete buildings in the European exposure model (as a function of their design code level and location). Figure 4 shows the number of buildings with code level CDL and CDM in the European exposure model and the distribution of lateral force coefficients within each country.

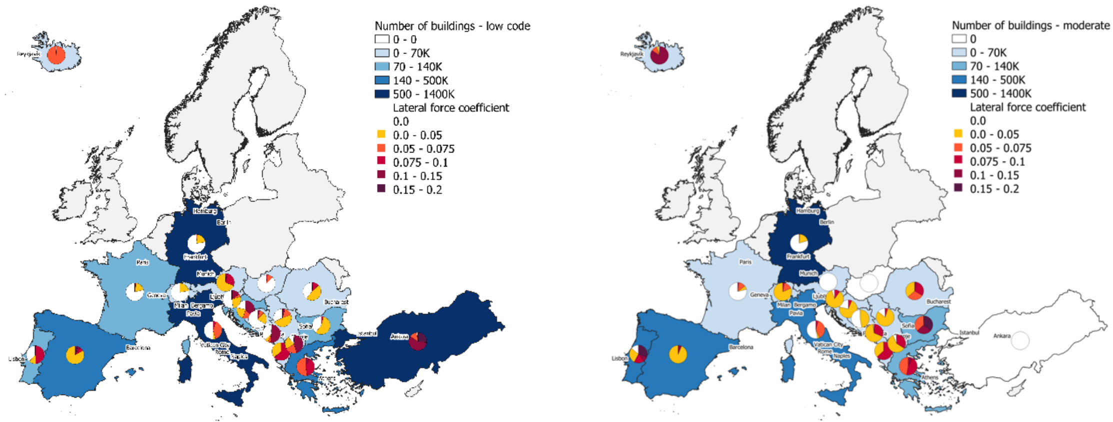


Figure 4. Map of the number of buildings with code level CDL (left) and CDM (right) in the European exposure model and the distribution of lateral force coefficients (for mid-rise RC frame buildings on medium soil) within each country. (Note that the countries in grey have not been considered in the study presented herein.)

These results also allow us to understand the areas of Europe with the most vulnerable reinforced concrete buildings, when compared with current seismic actions. Figure 5 presents the spatial variation of both the lateral force coefficient used in design between 1960 and 1970 together with the variation of peak ground acceleration (PGA) on rock with a 475-year return period according to the ESHM13 model (Woessner et al., 2015). Figure 6 provides a similar map showing the lateral force coefficients used in design between 1990 and 2000. If we consider typical design using modern codes, for the considered mid-rise reinforced concrete building with 0.5 seconds period on moderate soil, we might expect the lateral force coefficient to be of a similar value to the peak ground acceleration on rock (following spectral amplification of around 3 for medium soil and reduction using behaviour factors also of the order of 3). Hence, we would ideally want the map to represent the grey colours shown on the diagonal of the legend of these maps. The pink areas on these maps show areas where current seismic actions (according to the ESHM13 model) are higher than the lateral force coefficients used in design, and the darker the pink the larger the discrepancy. These are thus the areas where the most vulnerable buildings in Europe are expected to be located; see for example the areas in Italy, much of the Balkans and Turkey (before the 1970’s). On the other hand, the turquoise areas show where current seismic actions (according to ESHM13) are lower than the lateral force coefficient considered in design at the time.

As expected, there is a reduction in the deficiency of seismic actions from the 1970’s to the 1990’s, but there are still large areas of Europe where current probabilistic seismic hazard assessment leads to a higher level of design. It should be noted that these conclusions are based on the ESHM13 hazard model, which is currently undergoing revision, and the official seismic actions used for seismic design in each country differ from those in the ESHM13. Hence these results can only give a general indication of the level of deficiency in seismic actions across Europe, and comparisons at the national level should be undertaken. Such comparisons will be facilitated with the release of the data used to produce the maps presented herein.

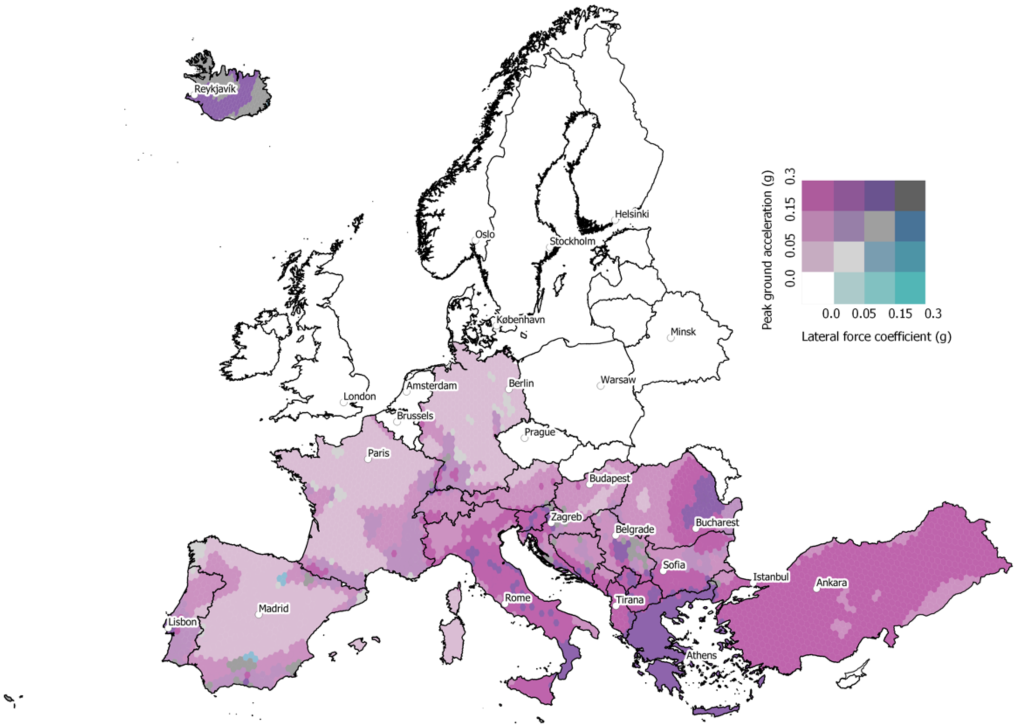


Figure 5. Bi-variate map presenting both the spatial variation of lateral force coefficient used in design between 1960 and 1970 and the peak ground acceleration on rock with a 475-year return period from the ESHM13 model (Woessner et al., 2015). (Note that the countries in white have not been considered in the study presented herein.)

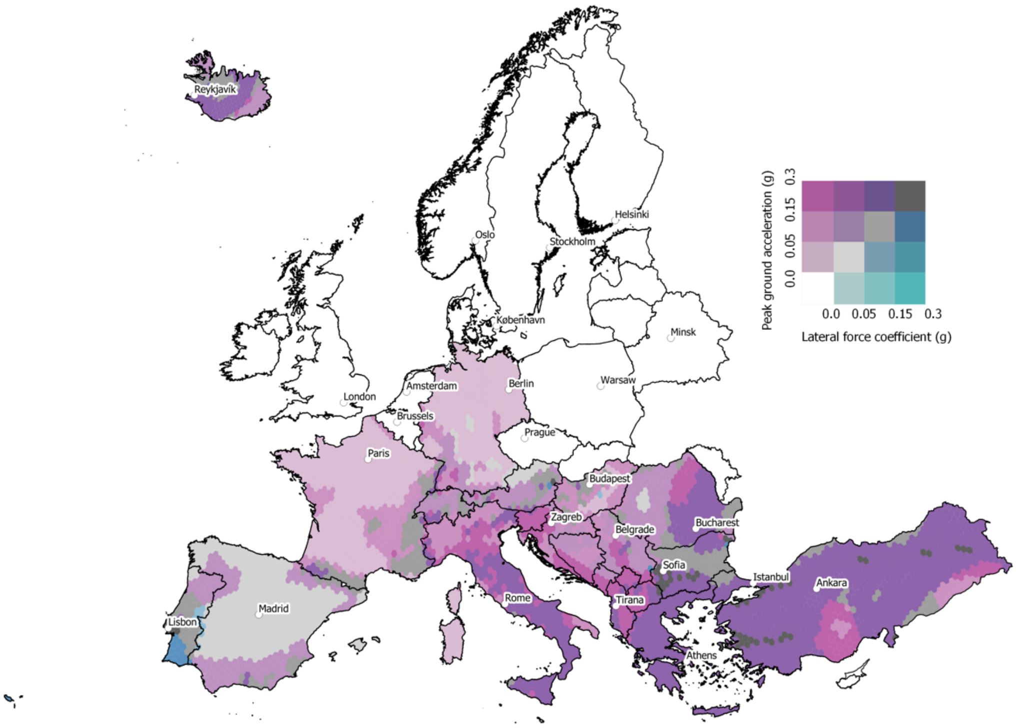


Figure 6. Bi-variate map presenting both the spatial variation of lateral force coefficient used in design between 1990 and 2000 and the peak ground acceleration on rock with a 475-year return period from the ESHM13 model (Woessner et al., 2015). (Note that the countries in white have not been considered in the study presented herein.)

Concluding Remarks

This paper has presented a model of the spatial and temporal evolution of seismic design of reinforced concrete buildings across Europe during the last century. This model has been developed using the knowledge of structural engineers from many countries in Europe and has been applied to the European exposure model (Crowley et al., 2020a) to better classify the vulnerability of reinforced concrete buildings within the European Seismic Risk Model (ESRM20), soon to be released through the risk services of the European Facilities for Earthquake Hazard and Risk (https://eu-risk.eucentre.it/seismic-risk/).

It is noted that, in some cases, simplifying assumptions have had to be made to develop the model presented herein, given that the focus is at the European level and thus it has not been possible to implement all changes made to the codes and seismic zonation maps. An attempt has been made to identify the codes which led to the most important changes in lateral force coefficients in each country. Nevertheless, if any readers have any feedback on the assumptions and values presented herein (and in the supplementary material) they are invited to share their feedback and become one of the contributors to the European Seismic Risk model[5].

It has been found that around 60% of the reinforced concrete buildings in the exposure model have been designed to some level of seismic action, with 85% having been designed to low or moderate levels of seismic design. When selecting the design codes to consider for the model, some consideration was given to the date after which widespread adoption/enforcement of codes was applied within a given country, but it should also be considered that in many countries buildings have been constructed without code compliance. This aspect is not currently considered in the exposure model and has been accounted for in the vulnerability models through the use of so-called 'quality factors'. Evaluation of the level of code enforcement and compliance in European countries deserves further attention in future updates to the European Seismic Risk Model, to allow country-specific quality factors to be assigned during the development of the vulnerability models.

A detailed investigation into the values of lateral force coefficients applied in the selected design codes across Europe was also undertaken herein to better represent the relative vulnerability of reinforced concrete buildings in the exposure model. In future updates to the exposure model, further attention will need to be given to the CDH buildings, in particular for what concerns the year of enforcement and the ductility classes that have been most frequently adopted across Europe.

In this paper some initial insights are provided into the areas of Europe where the seismic design of reinforced concrete buildings is highly deficient when compared with the seismic actions expected by today's standards, which for the older building stock covers much of Europe, with particularly high deficiencies in a significant proportion of Italy, much of the Balkans and Turkey. These are the regions in Europe where further attention to strengthening and retrofitting of reinforced concrete buildings should be prioritised. The ESRM20 model will be able to provide a quantitative assessment of the contribution of these buildings to the

[5] https://eu-risk.eucentre.it/contributors

losses in these countries, and it will be possible to undertake cost-benefit studies to assess the impact of upgrading these buildings to modern design standards.

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Conflicts of interest/Competing interests

Not applicable

Availability of data and material

The following GitLab repository includes the Shapefiles of the maps for each country with distribution of lateral force coefficients:
https://gitlab.seismo.ethz.ch/efehr/esrm20_exposure/-/tree/master/seismic_design_shapefiles
The data of Figure 3 is also available through the 'Evolution of European Seismic Design Levels Viewer' at the following URL: https://maps.eu-risk.eucentre.it/map/european-seismic-design-levels (Crowley et al., 2020b)

Code availability

Not applicable

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Appendix

This Appendix provides the full details for the design codes provided in Table 1.

Albania

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Austria

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Bulgaria

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Cyprus

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France

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Germany

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