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The European Seismic Risk Model 2020 (ESRM20)

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ABSTRACT

This study describes the development of the various components of the European Seismic Risk Model 2020 (ESRM20) which will be able to generate, using open-source software developed by the GEM Foundation (the OpenQuake-

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engine), a number of Europe-wide risk metrics including average annualised human and economic losses (AAL), probable maximum losses (PML), and risk maps showing the losses for specific return periods or scenario events. The latest developments towards pan-European exposure models for residential and non-residential buildings and fragility/vulnerability models for damage, economic loss and casualty assessment will be presented. For engineered buildings within the exposure model (reinforced concrete, steel), a simulated design is undertaken using the key aspects of seismic design codes in force across Europe over the past 100 years. The designed MDOF building is then transformed to a SDOF model and nonlinear dynamic analyses are run using a large number of ground motion records, after which cloud analysis is used to develop the fragility functions. For non-engineered buildings (unreinforced masonry, confined masonry, adobe), the SDOF models have been directly developed from simplified formulae, experimental tests and previous studies. Collaboration from local experts at various stages of the model development, initiated through workshops, is an important component of the model, as well as the extensive calibration and validation.

Keywords: pan-European seismic risk, exposure, vulnerability, socio-economic impact

INTRODUCTION

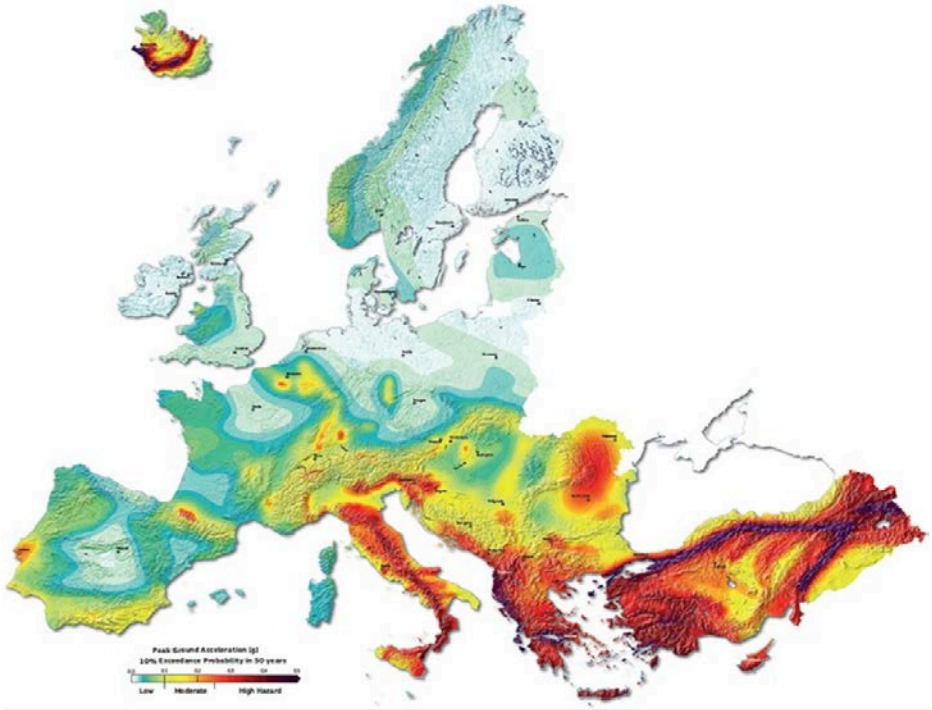
Over the past 20 years, European researchers have worked together on a number of projects dealing with various aspects of seismic risk assessment, and now as part of the research project "SERA" – Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe – a probabilistic seismic risk model across the European territory is being developed for the first time. This European Seismic Risk Model will be released in 2020 and will be an open and dynamic risk model that will be collaboratively updated and improved throughout the years. The first version of the model is being developed by a core team of researchers that are working with a number of local experts from countries across Europe which are engaged through workshops, meetings, online tools and email exchanges.

A probabilistic seismic risk assessment (PSRA) involves the estimation of the probability of damage and losses resulting from potential future earthquakes. This damage and loss might occur to buildings, infrastructure, people or even the environment. In simple terms, a PSRA involves the calculation and convolution of seismic hazards (surface ground shaking), fragility/vulnerability functions for each element at risk, and exposure models, describing primarily the location, building classes and value of all elements at risk. An overview of the current status of all components of the European risk model is presented herein including the latest developments towards pan-European exposure models for residential, commercial and industrial buildings and fragility/vulnerability models for damage, economic loss and casualty assessment.

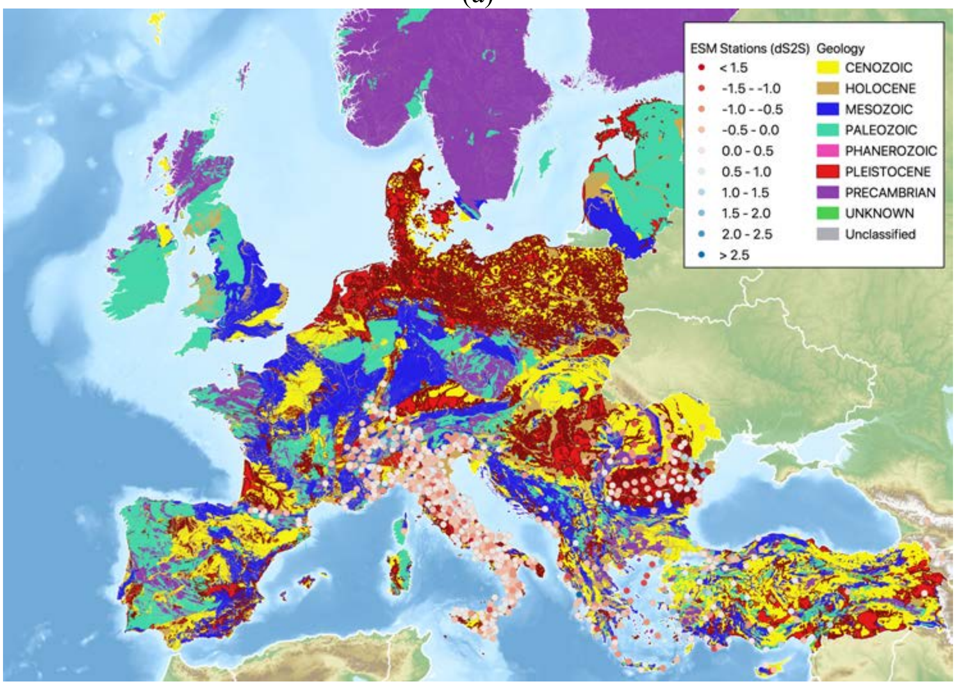
HAZARD AND SURFACE GROUND SHAKING

An update of the 2013 European seismic hazard model (ESHM13: Woessner *et al.*, 2015) is also being undertaken within the SERA project, and will provide the estimates of surface ground shaking for the risk model. Fig. 1 shows the reference PGA map on rock from ESHM13, though it is noted that the model also provides the spectral ordinates at a wide range of periods of vibration. The updated model will also cover additional intensity measures including *AvgSa*, defined as the mean of the log spectral accelerations at a set of periods of interest (Kohrangi *et al.*, 2017), Arias Intensity, and PGV.

Two key approaches are being simultaneously explored for this paper for pan-European site amplification of ground shaking: i) the correlation of proxies (e.g. geology, DEM) with Vs30 (as the latter is the parameter that the majority of modern GMPE's require as input for site amplification) (e.g. Wald and Allen, 2007; Vilanova *et al*. 2018; Lemoine *et al*., 2012), and ii) the development of a site response model that relates similar proxies directly to surface ground shaking through the δ_{S2S} term (i.e. site-to-site residual) in the ground motion model (Weatherill *et al*., 2019). This latter approach leverages upon the European Strong Motion database and flatfile (Lanzano *et al*., 2019) in which there can be found a significant increase in the number of strong motions stations for which multiple events have been recorded. It then attempts to calibrate the relationship between the measured amplification at a station and local site parameters that can be determined at a regional scale, adjusting the uncertainties accordingly.



(a)



(b)

Figure 1. (a) European seismic hazard model (ESHM13) results of peak ground acceleration (PGA) for a 475 year return period and a reference rock condition of Eurocode 8 type A (Vs_{30} = 800m/s) (Giardini *et al.*, 2013), (b) Map of harmonized European geology, derived from OneGeology (http://www.europe-geology.eu/onshore-geology/geological-map/onegeologyeurope) and Promine (http://promine.gtk.fi/) project data, showing the δ_{S2S} values at the European Strong Motion (ESM) stations

RESIDENTIAL AND NON-RESIDENTIAL EXPOSURE MODELS

The residential and non-residential exposure models have been derived based on the latest national housing censuses, socio-economic indicators (e.g. labour force, population and floor area per worker per economic sector), and inference rules developed by local experts. A common classification scheme (i.e. taxonomy) is being used to describe the buildings (see Crowley *et al.*, 2017a). By using a single classification scheme, it is possible to ensure that fragility/vulnerability models for specific elements at risk can be easily mapped to the information within the exposure models (that provide the location and value of those elements at risk) and that may be developed by different parts of the engineering community. The building taxonomy is based on the latest version (v2) of an international standard (the GEM Building Taxonomy: Brzev *et al*., 2013) and allows buildings to be classified according to a number of structural attributes. The main attributes that have been selected for the consistent definition of structural systems across Europe are as follows:

- main construction material,
- lateral load resisting system,
- number of storeys,
- seismic design code/lateral load coefficient (for engineered buildings).

The specific details related to the development of residential and non-residential exposure models are provided in the following sections.

Residential Buildings

The development of the European residential exposure model follows four main steps: i) definition of building classes (as mentioned above), ii) mapping census data to building classes (described in further detail below), iii) mapping dwellings to buildings, and iv) estimation of replacement costs and number of occupants. The latter two steps are described in more detail in Crowley *et al*. (2018a).

Population and housing census statistics usually provide information related to living conditions such as the number of dwellings and physical housing attributes that exist in a given area. Some countries also carry out a separate Building Census. However, the information that is used to describe each dwelling/building in such censuses varies across the different countries, and may not cover all of the features required to characterize a structure according to its potential seismic performance. Statistics are available on just dwellings/households in some countries, whereas in others the data on buildings is also available. The oldest census data in Europe is from 2001 (for Lithuania, Luxembourg, Slovakia, United Kingdom), and the latest is from 2017 (for Norway, Netherlands). Some countries have detailed information on the structural characteristics of the buildings through a separate Building Census (e.g. Portugal, Turkey, Greece), whereas in others only the type of the dwelling (single-family or multi-family) or only the predominant material of the exterior walls and year of construction is available (e.g. Moldova, Croatia). For these latter countries, the contribution of local experts becomes of fundamental importance. By carefully exploring the information provided by the census of each country, it becomes apparent that in many cases the information within the census can be associated to more than one building class. For example, dwellings whose predominant exterior wall material is defined as clay bricks could be assigned to reinforced concrete infilled moment-frame, to confined masonry or unreinforced masonry structures. The percentage of the number of buildings in each class should be ultimately informed by the distribution of these three types of structures (possibly also as a function of the number of storeys, and whether the area is urban or rural), as provided by the local experts.

Based on the year of construction, additional attributes related to the seismic design are also assigned. A detailed study of the temporal and spatial evolution of seismic design across Europe has been undertaken in order to identify, for each country, the type of seismic code (D: absence of seismic design, C: low-code, designed for lateral resistance using allowable stress design, B: moderate code, designed for lateral resistance with modern limit state design and A: high code, designed for lateral resistance coupled with target ductility requirements) and lateral load coefficients (i.e. percentage of weight that needed to be resisted laterally) for which reinforced concrete and steel buildings from different eras in different regions within the country were designed. Fig. 2 shows an example of the evolution of seismic design codes across Italy (from D to A) and the lateral force coefficients that were used in seismic design (for one storey buildings) across the country over different periods of time. Up until 2004 the lateral forces were explicitly prescribed in the code (or were simply calculated as a function of number of storeys and seismic zone), whereas in 2004 the seismic zonation was provided in terms of peak ground acceleration (PGA) that was used to anchor a spectral shape for different soil classes. In order to calculate lateral load coefficients for comparison with the previous maps, the PGA for each zone has been multiplied by the amplification factor for soil class B and the spectral amplification at 0.5 seconds, divided by a ductility factor of 3.5 (assumed to be a reasonable average value for reinforced concrete buildings).

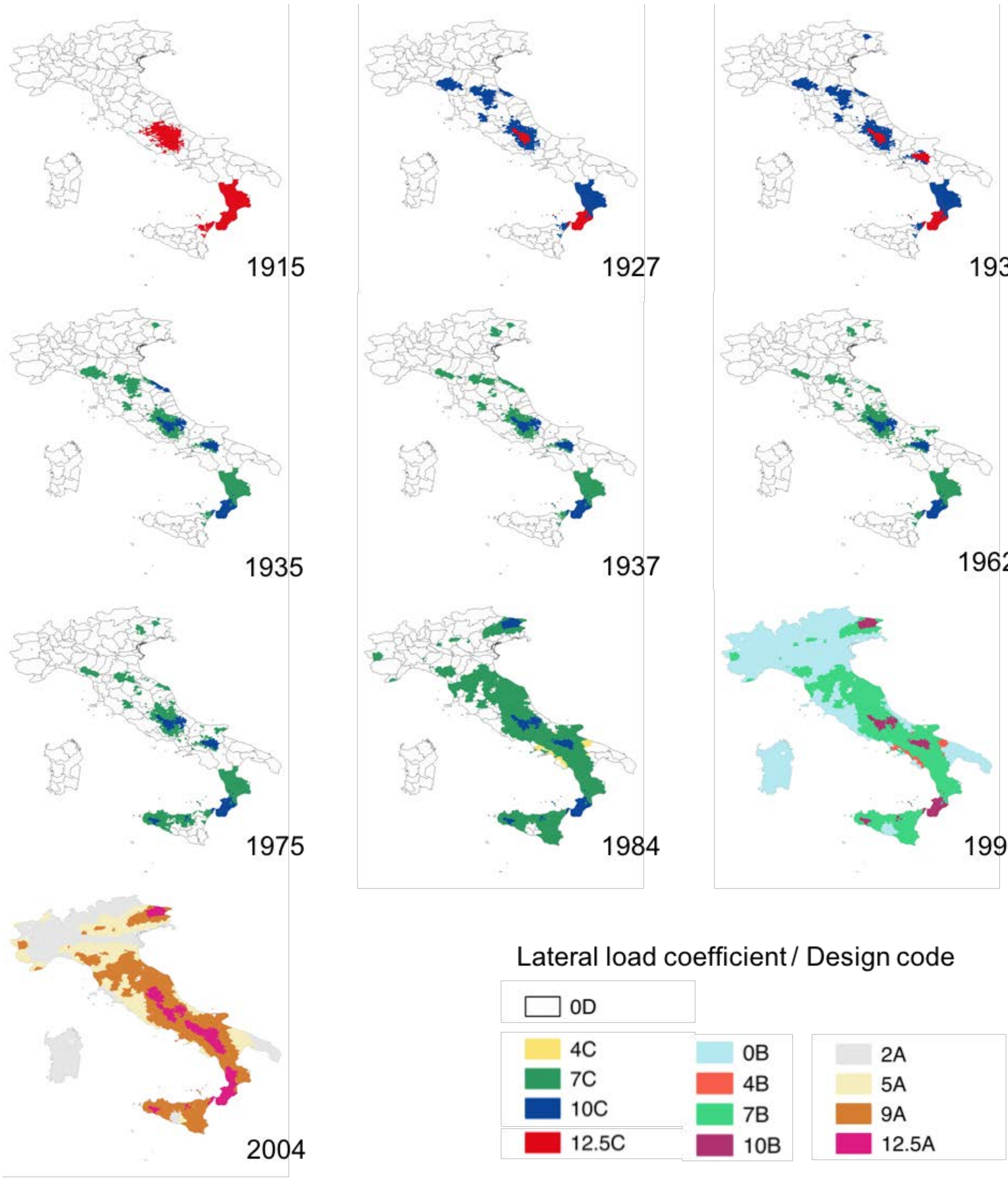


Figure 2. Evolution of seismic design codes in Italy (mainly adapted from Di Pasquale *et al*., 1999a; 1999b) showing the changes in lateral load coefficient (in percent) and type of design code (D to A)

Occupancy can also be used to distinguish between building classes; for example, apartments are usually found in higher buildings constructed with reinforced concrete or load-bearing masonry, whereas detached or terraced single-family houses are usually low-rise and often built with unreinforced masonry. These relationships between the attributes used in the census data, and the final list of building classes are referred to as *mapping schemes*. The development of the mapping schemes closely follows the methodology thoroughly described in Yepes-Estrada *et al.* (2017). The advantage of this approach is that it can be continuously refined based on additional input from local experts. So far, mapping schemes have been developed for all European countries using both local expertise and the following sources of information:

NERA project (https://cordis.europa.eu/project/rcn/96282/factsheet/en); SYNER-G project (http://www.vce.at/SYNER-G/) (in particular Reference Reports 2 and 3); BPIE – Improving the Energy Performance of Buildings across Europe (http://www.bpie.eu); TABULA - Typology Approach for Building Stock Energy Assessment (http://episcope.eu/iee-project/tabula/); World Housing Encyclopedia (WHE) (http://www.world-housing.net/); peer-reviewed publications; United Nations Statistics; Global Exposure Database from GEM; PAGER building inventory database (https://pubs.usgs.gov/of/2008/1160/. Fig. 3 shows the distribution of lateral-load resisting material in residential buildings in each country in Europe according to the current status of the European exposure model.

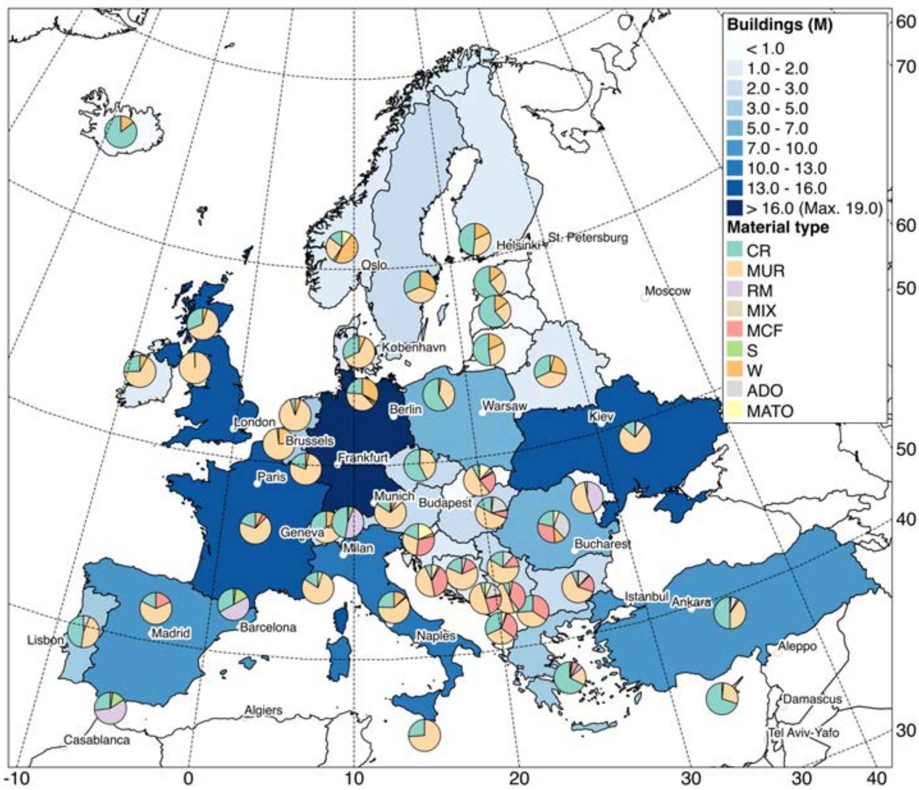


Figure 3. Number of buildings and distribution of lateral load resisting material for residential buildings across Europe. Note that CR: reinforced concrete, MUR: unreinforced concrete, RM: reinforced masonry, MIX: mixed materials, MCF: confined masonry, S: steel, W: timber, ADO: adobe, MATO: other material.

Non-residential Buildings

Non-residential buildings fall into two broad categories of (light) industrial buildings and commercial buildings. Few national statistics departments provide exposure information for non-residential buildings at regional or national scale. Unlike the residential building stock, that relies predominantly on national housing census data, the industrial and commercial building stock when not captured in a separate National Building Census needs to rely on secondary sources such as economic census surveys, studies related to the energy efficiency of buildings, European statistics platforms or the judgment of local experts.

The majority of the national census databases, with only few exceptions (e.g., Greece, Turkey), do not provide information on the number of industrial buildings. Therefore, for the cases where no data were found, the number of industrial establishments or enterprises was used as a proxy to define the number of industrial buildings. The number of industrial establishments/enterprises is commonly found at the national level in the structural business statistics of each country, categorized by industrial activity. Herein, the manufacturing, the mining and quarrying and the construction sectors, which are usually reported in the structural business statistics, were assumed to constitute the industrial building stock.

The total area of the industrial buildings in each European country on a 30 arc sec resolution was obtained from Sousa *et al.* (2017) and it was further used in order to spatially distribute the number of industrial establishments/enterprises at the aforementioned resolution. A mapping scheme including the most likely building classes associated with industrial buildings was then developed for each country. To this end, the European countries were initially assigned in groups of countries with similar building stock characteristics, as suggested by Wyss *et al*. (2013). Reference countries with available information on the attributes of the industrial buildings were selected for each group, based on which the mapping scheme of the remaining countries within the group was developed. The main sources of information were the census databases, peer-reviewed publications, such as Petruzzelli *et al.* (2012), the PRECASTEEL project (Braconi *et al.*, 2013) and personal communications with local experts.

Whilst some national statistics departments do contain information concerning the total number of commercial buildings (e.g. Norway, Italy), or the number of commercial facilities at the smallest division (e.g. Greece), the majority of countries in Europe do not. In the vast majority of the nations, the total number of buildings was collected using the EU buildings database (e.g. Ireland, Latvia, Belgium) (https://ec.europa.eu/energy/en/eu-buildings-database) or using assumptions based on the number of enterprises/establishments/businesses (e.g. Albania, Portugal, Switzerland). The number of commercial facilities is usually related with the type of sector – services – and the type of business: wholesale and retail trade, repair of motor vehicles and motorcycles, accommodation and food services, information and communication, financial and insurance activities, real estate activities, administrative and support service activities, arts, entertainment and recreation and other service activities. These data are then organized according to three categories for the purposes of the European risk model: offices, wholesale and retail trade and hotels and restaurants. Fig. 4 presents the current status of the European commercial exposure model.

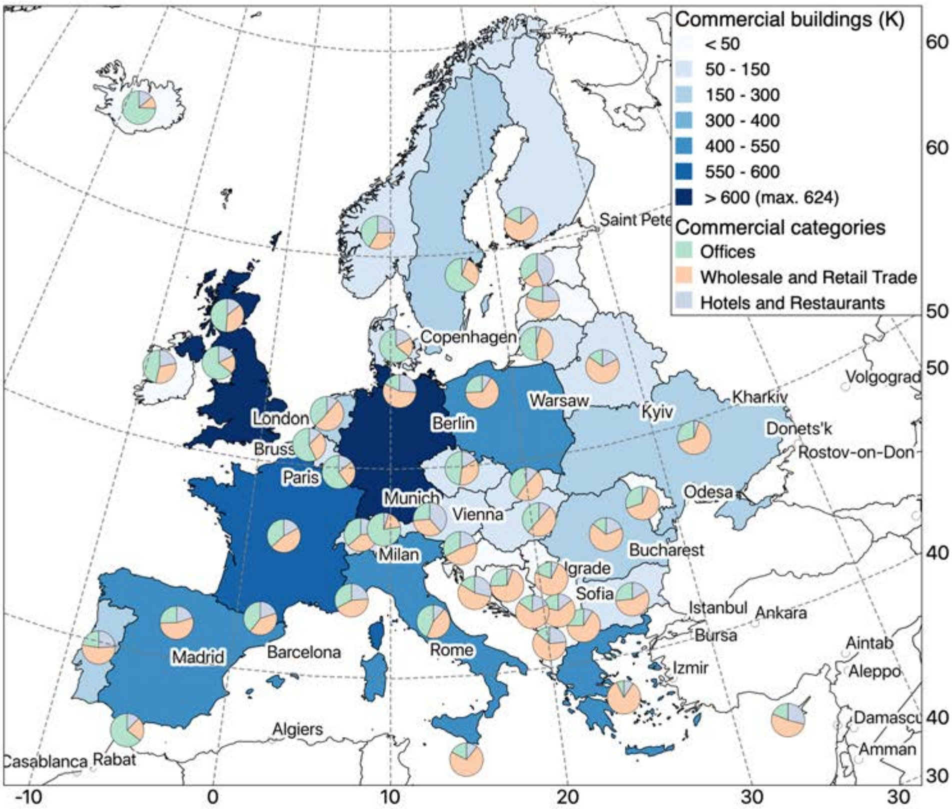


Figure 4. Number of commercial buildings and distribution across sectors in the European exposure model

In cases where the number of commercial facilities is only available at the national level (e.g. using EU building datasets), it is necessary to distribute these facilities within the administrative divisions of the countries in order to improve the spatial resolution of the exposure model. The assignment of the facilities across these administrative divisions relies essentially on economic census surveys, which provide demographic data concerning the work force, as the number of employees or other economic indicators related to the services sector and commercial businesses. A mapping scheme establishing the most likely building classes associated with each one of these three categories is then developed based on local expert judgment and satellite imagery.

PHYSICAL VULNERABILITY

Physical vulnerability is defined as the probability of loss to a structure, given a level of ground shaking. For the European risk model, physical vulnerability models are being developed by combining analytical fragility models (which provide the probability of exceeding different levels of damage under a given level of ground shaking) with semi-empirical consequence models that relate the damage level with the probability of loss (due to repair costs or loss of life). For the engineered buildings in the exposure model, a simulated design is undertaken for the design codes (A to D) described previously and for a range of lateral load coefficients. The methodology has been used by various researchers in Europe (see e.g. Verderame *et al*., 2010 and Borzi *et al*., 2008a). The designed MDOF building is then transformed into a SDOF oscillator and nonlinear dynamic analyses are performed using a large number of ground motion records. Linear regression of the displacement response (Fig. 5) is then used to develop the fragility functions for damage states from slight damage, DS1, to near collapse, DS4 (see e.g. Crowley *et al*. 2017b; Crowley *et al*., 2018b). It is noted that the points with displacement above DS4 shown in Fig 5 are censored in the regression (see e.g. Stafford, 2008) as they exceed the ultimate limit state of the SDOF oscillator and are thus not reliable estimates of displacement response. For non-engineered buildings (unreinforced masonry, confined masonry, adobe), the SDOF models have been directly developed from simplified formulae, experimental tests and previous studies (e.g. Calvi 1999; Borzi *et al*., 2008b; Lagomarsino and Cattari, 2014).

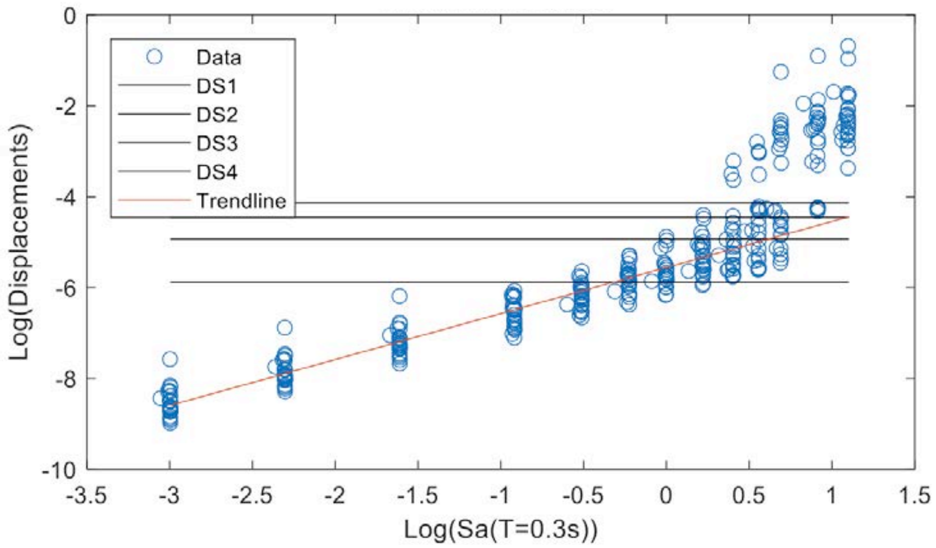
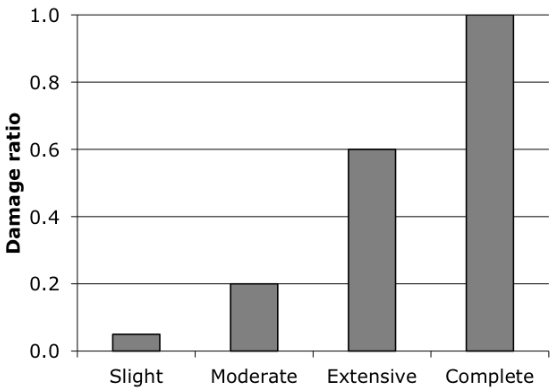


Figure 5. Example linear regression (red line) of the SDOF displacement responses (blue circles) and damage state thresholds DS1 to DS4 (black lines).

Various consequence models exist to relate the damage level with the ratio of cost of repair to cost of replacement (e.g. Di Pasquale and Goretti 2001; Bal *et al*., 2008; Kappos *et al*. 2006; FEMA 2004). Fig. 6 shows the probabilistic model that has been adopted by the Global Earthquake Model (GEM) in the Global Risk Model released in December 2018 (https://www.globalquakemodel.org/gem). This model is being tentatively used in the European risk model given that GEM has extensively tested the model against observed economic ground-up losses in Europe, as provided by Munich Re's NatCatService and the United States National Oceanic and Atmospheric Administration (NOAA).



Damage State	Mean	CoV
Slight	0.05	45%
Moderate	0.20	30%
Extensive	0.60	20%
Complete	1.00	0%

Figure 6. Consequence model for direct loss due to damage (Yepes and Silva, 2017)

The consequence model for fatalities is still undergoing development and draws from key research undertaken by Coburn and Spence (2002), FEMA (2004) and So and Pomonis (2012). Fatality risk is related to the collapse risk of buildings, the predominant collapse mechanisms and the ratio of a collapsed building's indoor volume loss, but analytical fragility models can only reliably predict near collapse damage states (DS4 herein). Hence, there is a need to estimate the percentage of buildings with a DS4 damage state that may effectively collapse, and the associated ratio of indoor volume loss. The input for the latter needs to draw from observed collapsed mechanisms from past earthquakes (Fig 7) and associated empirical life loss data (as further discussed in the next section).

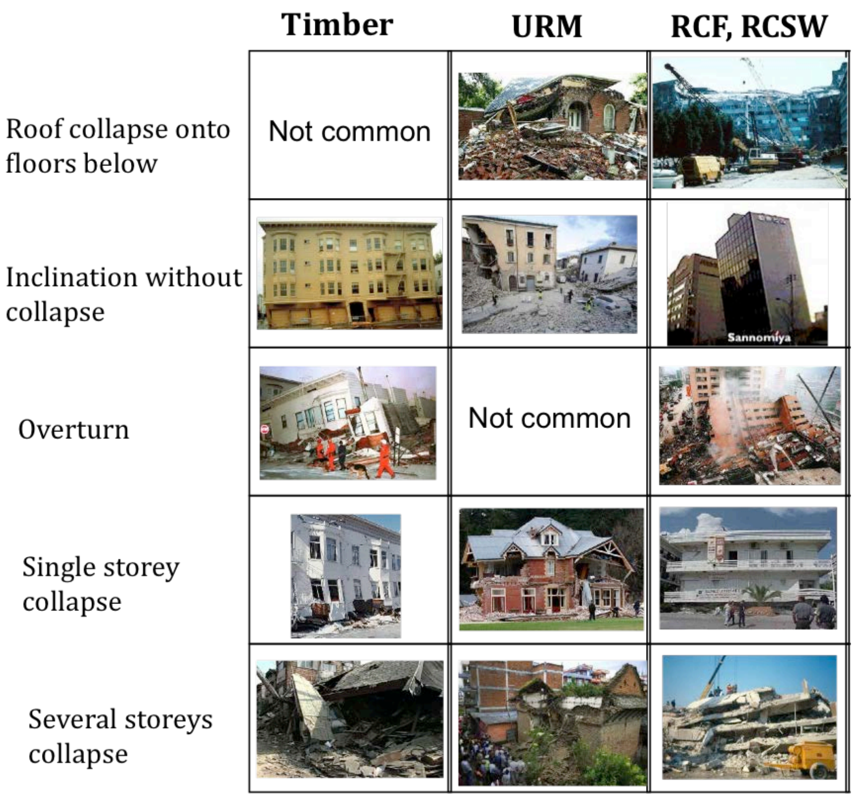


Figure 7. Predominant collapse mechanisms for European building classes (URM: unreinforced masonry, RCF: reinforced concrete frame, RCSW: reinforced concrete shear walls)

TESTING AND EVALUATION

The physical fragility and vulnerability models being developed at the European scale will undergo a significant amount of testing, evaluation and potential calibration before the European risk model is released. Site amplification proxies will be also tested at regional and local (i.e. city) scale. In all cases, the impact of the uncertainties involved on the testing will be discussed. All of the European risk model outputs will be calculated using the OpenQuake-engine (see Pagani *et al*., 2014; Silva *et al*., 2014). Another feature of the OpenQuake-engine is that the scenario calculator makes use of publicly available information from the USGS ShakeMap system so that the observed ground shaking from various past events can be used together with the proposed fragility and vulnerability models to predict the losses from these events (Silva and Horspool, 2019). In order to evaluate the predicted losses, the observed damage and loss from a number of past European events is thus being collected, considering databases such as the Global Earthquake Model's Consequences Database (So, 2014), the Italian Department of Civil Protection's Da.D.O database (http://egeos.eucentre.it/danno_osservato/web/danno_osservato), the Earthquake Impact Database (https://earthquake-report.com/), the Cambridge Earthquake Impact Database (http://www.ceqid.org), the Significant Earthquake Database of the National Oceanic and Atmospheric Administration (NOAA: https://www.ngdc.noaa.gov/hazard/earthqk.shtml), Emergency Events Database of the Université Catholique de Louvain (EM-DAT: https://www.emdat.be/), and the PAGER-CAT losses database (Allen *et al*., 2009, https://earthquake.usgs.gov/data/pager/references.php).

CONCLUSIONS

A pan-European seismic risk model will be released in 2020 through a collaborative effort between the SERA project, the Global Earthquake Model and a number of researchers and academics across Europe. This paper has described the main updates related to the exposure and physical vulnerability models that are currently being undertaken. All of the data, models and results developed during the project will be assigned a Creative Commons open data license (https://creativecommons.org/licenses/) and will be shared with the community through the European Facilities for Earthquake Hazard and Risk platform (www.efehr.org). These European models will also be used for updates to GEM's Global Seismic Risk Model. One of the main objectives of sharing the data and models is to allow others to test them, identify gaps in the data, and improve the future of European seismic risk modelling.

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