TOWARDS THE DEVELOPMENT OF A UNIFORM SEISMIC VULNERABILITY AND RISK MODEL IN EUROPE. THE CASES OF ATHENS AND THESSALONIKI, GREECE.

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Abstract

Seismic vulnerability and risk assessment are of major importance for decision-making with respect to the reduction of earthquake-induced losses at local, urban, national and even continental scale, as well as for the insurance industry. In the framework of the H2020 EU SERA project (http://www.sera-eu.org/en/home/), an effort is being made to develop and offer to the European research community an open access uniform seismic vulnerability and risk model at European scale. The model comprises of three main components, i.e., seismic hazard, building exposure model and physical - socioeconomic vulnerability models. In this study we aim to validate the proposed model by comparing the computed losses with the recorded ones from two major past earthquakes; the Athens 1999 M6.0 earthquake and the Thessaloniki 1978 M6.4 earthquake. Seismic hazard in these two validation studies is estimated using fault rupture models with the open-source earthquake hazard and risk software OpenQuake or obtained from the corresponding USGS shakemaps. For the exposure model of the validation analyses we use the building inventory which corresponds to the 1999 and 1978 situation of the building stock for Athens and Thessaloniki. The taxonomy scheme of the Global Earthquake Model (GEM) is applied (Brzev et al., 2013), which allows buildings to be classified according to several structural attributes, i.e., main construction material, lateral load resisting system, number of storey, age of construction and seismic design level. For the vulnerability model we apply the fragility curves proposed by GEM (Martins and Silva, 2018). This work is a valuable contribution to the efforts towards the generation of a uniform European-wide seismic risk model, which, in its turn, can contribute to the successful management of the earthquake crisis in all its phases and to the efforts towards increasing the resilience of cities.

Keywords: seismic hazard; vulnerability; risk

1. Introduction

Seismic vulnerability and risk assessment are of major importance for decision-making with respect to the reduction of earthquake-induced losses at local, urban, national and even continental scale, as well as for the insurance industry. Particularly at urban scale, seismic risk assessment is crucial for the assessment of socio-economic impact of future earthquakes on a densely populated area, of potential interest for insurance and reinsurance industries, for the planning of effective actions for seismic risk mitigation and preparedness, for the improvement of decision making in support to emergency response and disaster management; and eventually for the optimization of retrofitting strategies [1].

In the framework of the H2020 EU SERA project (http://www.sera-eu.org/en/home/), an effort is being made to develop and offer to the European research community an open access uniform seismic vulnerability and risk model at European scale [2]. The model comprises of three main components, i.e., seismic hazard, building exposure model and physical - socioeconomic vulnerability models. The testing framework that is being set up to verify the model is described in detail in [2]. In this study we aim to verify the proposed model by comparing the computed losses with the recorded ones from two major past earthquakes; the Athens 1999 M6.0 earthquake and the Thessaloniki 1978 M6.4 earthquake. Seismic hazard in these two validation studies is either estimated using a fault rupture model with the open-source earthquake hazard and risk software OpenQuake or obtained from the corresponding USGS shakemaps. For the exposure model of the validation analyses we use the building inventory which corresponds to the 1999 and 1978 situation of the building stock for Athens and Thessaloniki. The taxonomy scheme of the Global Earthquake Model (GEM) is applied [3], which allows buildings to be classified according to several structural attributes, i.e., main construction material, lateral load resisting system, number of storey, age of construction and seismic design level. For the vulnerability model we apply the fragility curves proposed by GEM [4]. These models were selected over other models developed specifically for Greece, so as to achieve conformity across Europe within the SERA project This work is a valuable contribution to the efforts towards the generation of a uniform European-wide seismic risk model, which, in its turn, can contribute to the successful management of the earthquake crisis in all its phases and to the efforts towards increasing the resilience of cities.

2. Study areas

The uniform European seismic vulnerability model that predicts the seismic damage from actual seismic events, is applied herein to the cities of Thessaloniki and Athens, for Thessaloniki, 1978 and Athens, 1999 earthquakes, respectively.

Thessaloniki is the second-largest city in Greece, with over 1 million inhabitants in its metropolitan area and the financial center in Northern Greece. Its seismicity is mainly associated with the activity of the Mygdonia and the Anthemountas faults, which were responsible for severe destructive earthquakes with magnitudes up to 7 [5]. The latest major earthquake in Thessaloniki happened in June 1978 with an epicenter located at a distance of about 30km NE of the city and a magnitude of Mw 6.5. The earthquake caused 47 deaths [6], 37 of which due to the collapse of a 9-storey reinforced concrete building, a limited number of partial collapses, and slight to moderate damage to a large number of buildings [6].

Athens is the capital and the largest city of Greece. Athens dominates the Attica region and is one of the world's oldest cities. The broader area of Athens generally was characterized by low seismic activity, since no major earthquakes had been reported in historical catalogues. However, on September 7, 1999, at 11:56 GMT (14:56 local time), a strong earthquake of magnitude Mw 5.9 occurred very close to the capital of Greece, Athens. This event is the first reported at such close distance from the center of Athens (18 km) during instrumental period and caused the death of 143 people and the collapse of 100 buildings. The heaviest damage occurred close to the epicentral area, where maximum intensity was estimated to be of the order of IX (modified Mercalli-Sieberg scale) [7].

Both Thessaloniki, 1978 and Athens, 1999 earthquakes, revealed the high vulnerability of modern urban areas where most reinforced concrete buildings were constructed with almost no earthquake-resistant design criteria (post 1959 code). The extensive damages induced by the Thessaloniki, 1978 and Athens, 1999 events encouraged the development of a series of research studies aimed at improving the knowledge on the seismotectonic context, at providing a large-scale geophysical and geotechnical characterization for microzonation purposes, as well as at defining detailed vulnerability and exposure models for RC and masonry buildings [8-10].

Figure 1 shows the study areas at national and urban scales.

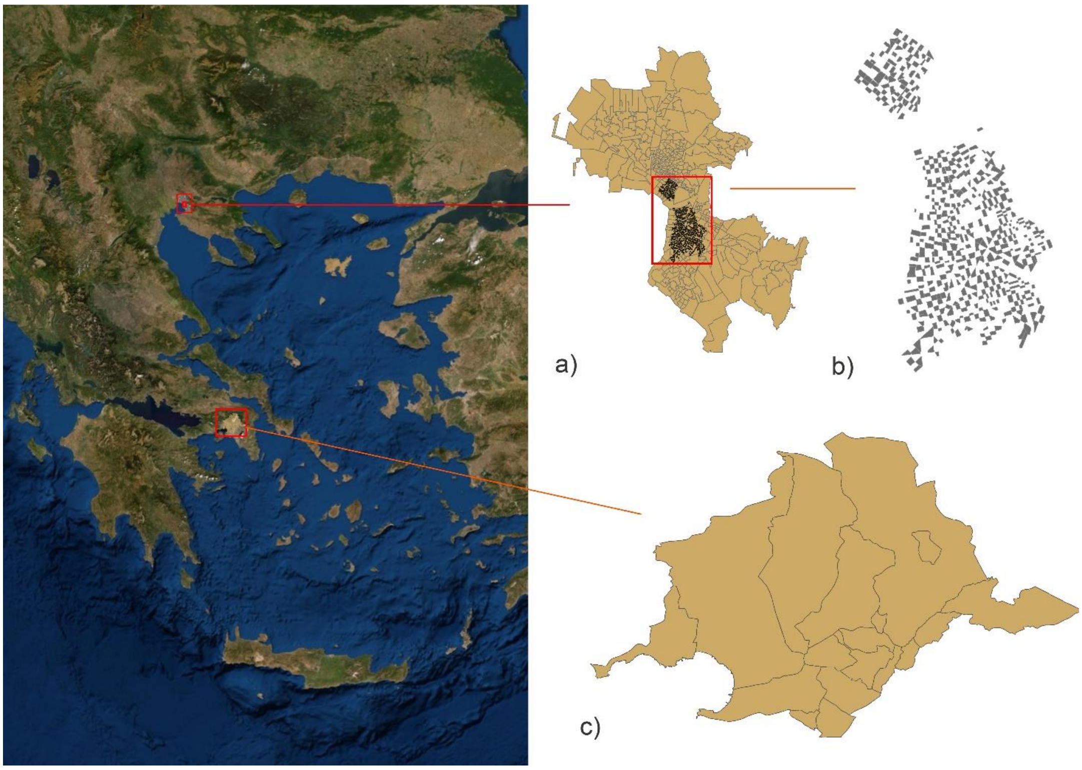

Fig. 1 – Location of the study area on the map of Greece. (a) Thessaloniki center (in brown) and (b) Earthquake 1978 study area (in black). (c) Athens center, Earthquake 1999 study area

3. Seismic hazard

In order to validate the seismic risk methodology, we used two seismic scenarios, which represent the two most destructive recent earthquakes that have affected the study areas, i.e. the Thessaloniki 1978 M6.4 earthquake for Thessaloniki and the Athens 1999 M6.0 earthquake for Athens. The two events were simulated in OpenQuake [11,12] as earthquake rupture scenarios. For the Thessaloniki 1978 earthquake, we used the fault rupture model by Roumelioti et al. [13], while for the Athens 1999 we applied the rupture model Roumelioti et al. [7]. Strong ground motion modelling was performed by means of the ground-motion prediction equation (GMPE) by Akkar and Bommer (2010) [14].

To account for local site conditions, the applied GMPE [14] uses as site parameter the $V_{s,30}$, i.e. the average shear wave velocity of the upper 30m of the soil profile, calculated from the total time needed for a shear wave to travel these 30m. To this end, we adopted, despite its disputed accuracy, the global slope-based $V_{s,30}$ model of USGS, which has been developed via correlation of $V_{s,30}$ to topographic slope using the methodology proposed by Wald and Allen [15]. The spatial distribution of $V_{s,30}$ for the two study areas is shown in Figure 2. It should be stressed that this $V_{s,30}$ model should only be applied for preliminary analyses and a more detailed site-specific model is required for a more accurate seismic risk assessment. According to the USGS $V_{s,30}$ model, most regions in Thessaloniki are classified with this intentionally simplified approach, as soil class B based on the EC8 soil classification scheme [16] with $V_{s,30}$ ranging between 361 and 800 m/s, while there is an additional zone close to the coastal area with softer soil materials classified as soil class C based on EC8. These values are in quite good agreement with more detailed $V_{s,30}$ models available for Thessaloniki [17]. Regarding Athens, the study area based on the USGS $V_{s,30}$ model has $V_{s,30}$ values ranging between 326 and 647 m/s, and is hence classified again as predominantly soil class B.

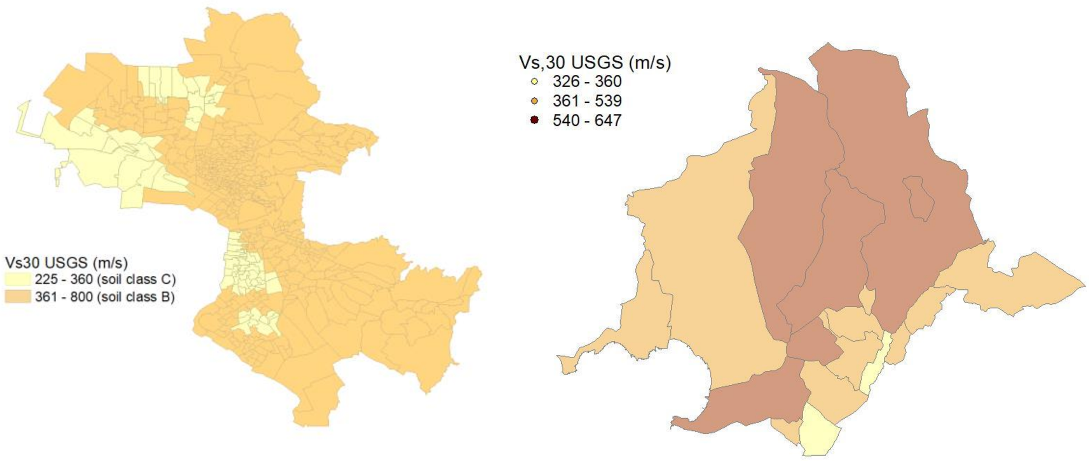

Fig. 2 – Spatial distribution of Vs,30 (m/s) for (a) Thessaloniki and (b) Athens according to USGS slope-based model

Figure 3 illustrates the spatial distribution of peak ground acceleration PGA (g) for Thessaloniki, obtained from the Thessaloniki 1978 scenario analysis with OpenQuake, using the fault rupture model by Roumelioti et al. [13], the Akkar and Bommer GMPE [14] and the USGS $V_{s,30}$ model shown in Figure 2a. PGA values from the USGS shakemap system [18], which is one of the most well established efforts to calculate and distribute ground shaking estimates and data shortly after the occurrence of significant seismic events, are superimposed on the map as dots. We observe that the PGA values estimated with the OpenQuake for the specific scenario range between 0.201 g and 0.404 g and are in quite good agreement with the available Shakemap values.

Likewise, Figure 4 compares the PGA values obtained for Athens study area from the Athens 1999 scenario analysis with OpenQuake, using the fault rupture model by Roumelioti et al. [7], the Akkar and Bommer GMPE [14] and the USGS $V_{s,30}$ model shown in Figure 2b, with the respective PGA values from the USGS shakemap system. The PGA values estimated with OpenQuake for the specific scenario range between 0.183 g and 0.365 g, which in this case are generally much lower than the available USGS Shakemap values, that can be as high as 0.65 g. The discussion on these differences is beyond the scope of this paper.

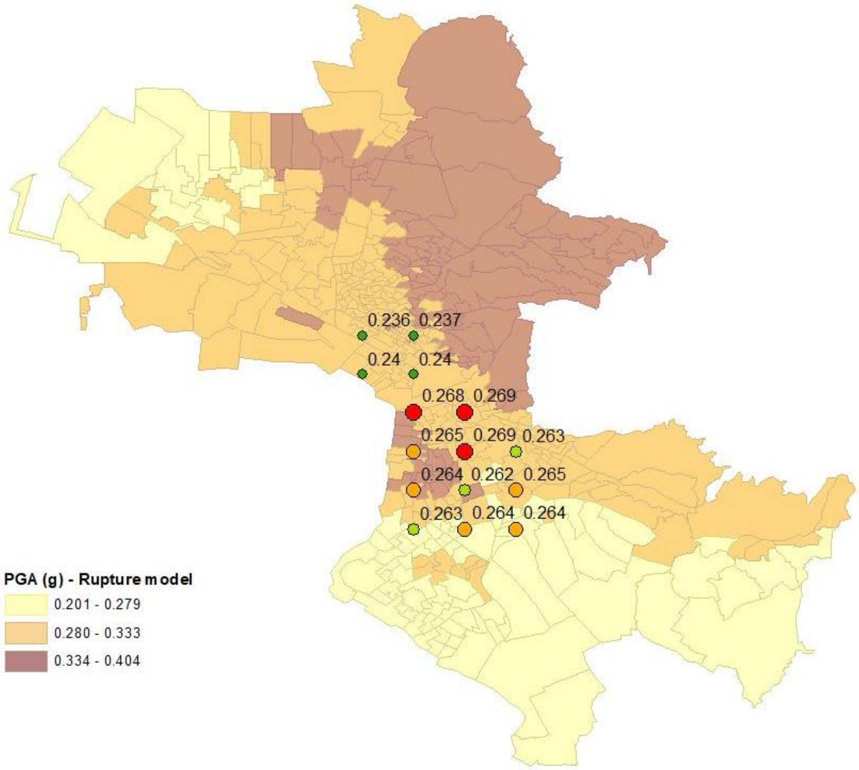

Fig. 3 – Thessaloniki 1978 M6.4 earthquake: Comparison between PGA values obtained from scenario analysis with OpenQuake using the fault rupture model by Roumelioti et al. [13], the Akkar and Bommer GMPE [14] and the USGS $V_{s,30}$ model shown in Figure 2a, and PGA values from the respective USGS shakemap.

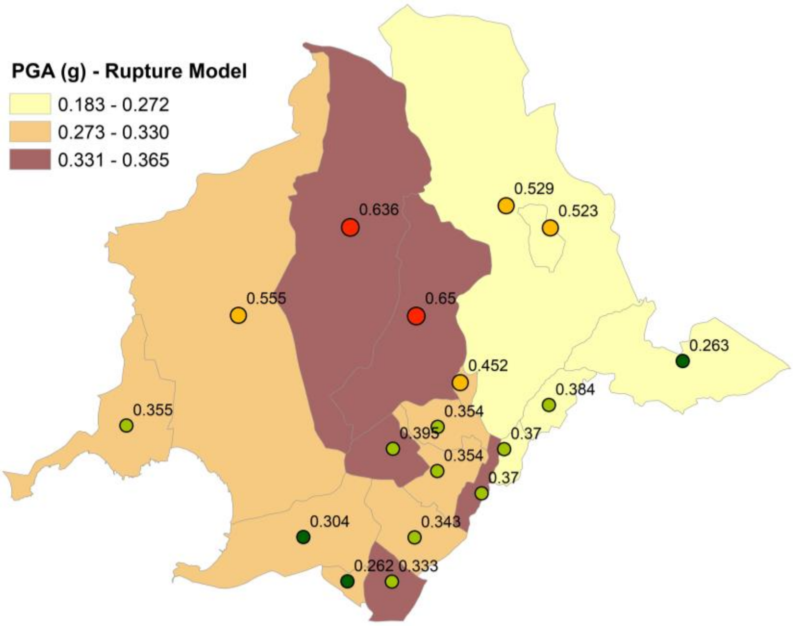

Fig. 4 – Athens 1999 M6.0 earthquake: Comparison between PGA values obtained from scenario analysis with OpenQuake using the fault rupture model by Roumelioti et al. [7], the Akkar and Bommer GMPE [14] and the USGS $V_{s,30}$ model shown in Figure 2b, and PGA values from the respective USGS shakemap.

4. Exposure models

All buildings of Thessaloniki 1978 and Athens 1991 were classified into different building classes following the GEM building taxonomy scheme [3] (Table 1), which allows buildings to be classified according to a number of structural attributes, i.e., main construction material, lateral load resisting system, number of storeys (height) and ductility level, which is herein assumed to be a function of the construction period and respective seismic design code in force.

For the Thessaloniki exposure model that corresponds to the 1978 situation we used the building inventory developed by Kappos et al. [19] for the area shown in black in Figure 1b, which is a combination of the 1991 census data, data from previous projects and in-situ work [20, 21]. The inventory includes 4400 buildings. For the Athens exposure model that corresponds to the 1999 (382518 residential buildings) situation we used the 2011 building census data, after removal of all buildings constructed after 1999.

Table 1 – Values of attributes of the GEM Building Taxonomy [3] currently used to describe the residential building stock of Thessaloniki

ATTRIBUTE	ELEMENT CODE	LEVEL 1 VALUE	ELEMENT CODE	LEVEL 2 VALUE
MATERIAL	CR	Concrete, reinforced	PC	Precast concrete
	MUR	Masonry, unreinforced	CL	Fired clay unit, unknown type
	MR	Masonry, reinforced	ST	Stone, unknown technology
	MCF	Masonry, confined	ADO	Adobe blocks
	MATO	Material, other	CB	Concrete blocks, unknown type
	W	Wood		
	S	Steel		
LATERAL LOAD-RESISTING SYSTEM	LWAL	Wall	DUL	Ductile, low
	LDUAL	Dual frame-wall	DUM	Ductile, medium
	LFM	Moment frame	DUH	Ductile, high
	LFINF	Infilled frame	DNO	Non-ductile
HEIGHT	H	Number of storeys above ground	HBET	Range of number of storeys above ground
			H	Exact number of storeys above ground
	SOS	Soft Storey Buildings		
DUCTILITY LEVEL	DUH	Period of construction: 1996-present		
	DUCM	Period of construction: 1986-1995		
	DUCL	Period of construction: 1960-1985		
	DNO	Period of construction: before 1959		

Figure 5 shows the main building typologies of the adopted Thessaloniki and Athens exposure models following the GEM Building Taxonomy [3]. Over 55% of the buildings in Thessaloniki study area are low-code reinforced concrete structures, with dual lateral load- resisting system and number of storeys above ground from 3 to 6+, whereas in Athens study area the most frequent building classes concern low-code reinforced concrete infilled frames, with number of storeys above ground from 1 to 5.

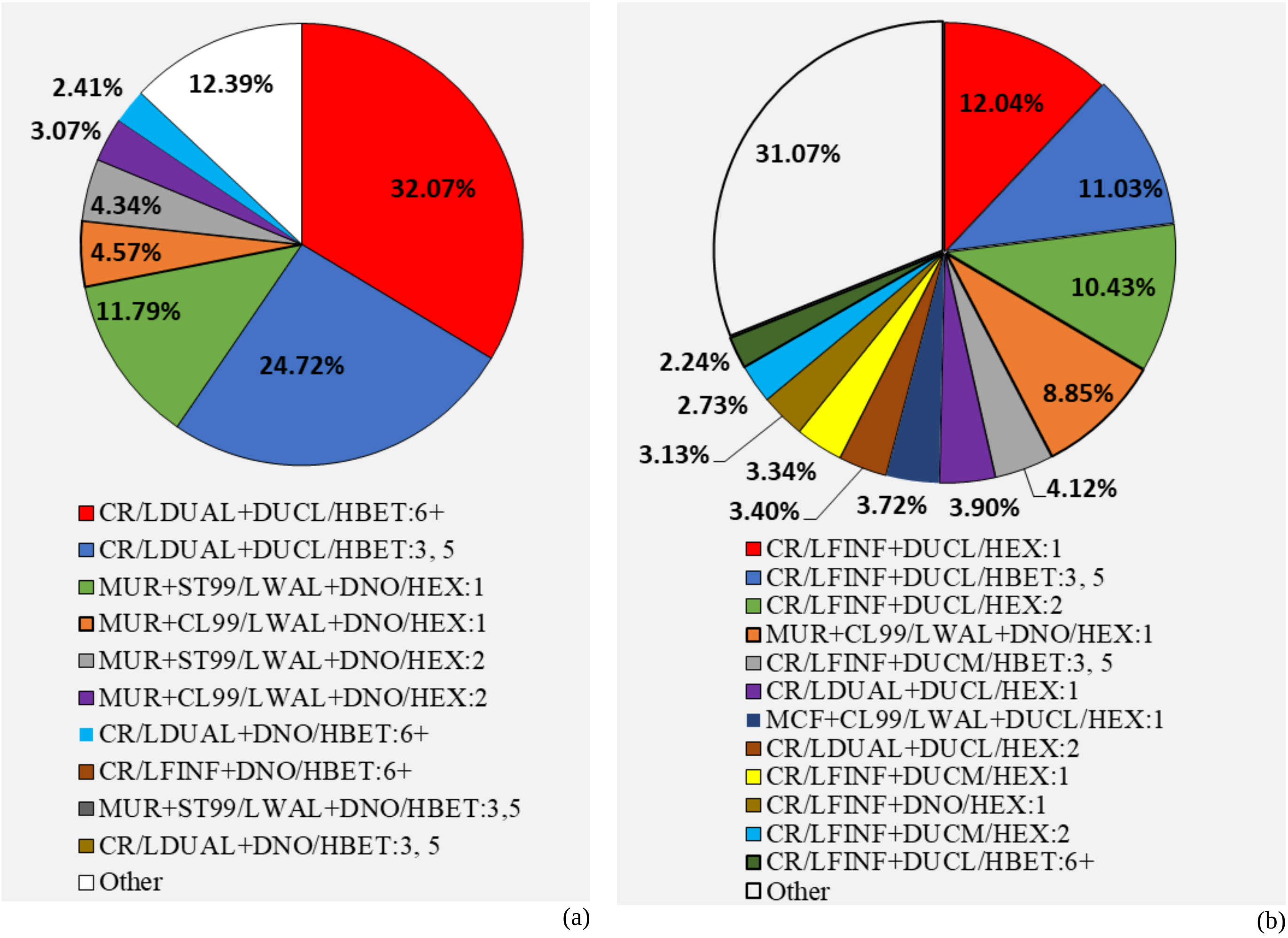

Fig. 5 – Most common taxonomies in (a) Thessaloniki 1978 and in (b) Athens 1999

5. Vulnerability

In the present study we adopted the GEM fragility models [4], which have been developed from the results of nonlinear dynamic analyses performed on equivalent SDOF systems representing each building class considered herein following a cloud analysis framework. Building-to-building and record-to-record variability were included in the analyses by considering large sets of capacity curves and ground motion records, respectively. For the generation of the fragility models the main assumptions are the following: i) the capacity for each building class was assumed to follow a multilinear model computed using the yield and ultimate displacements, ii) appropriate records were selected from various ground motion databases, iii) nonlinear dynamic analyses were performed in numerical models, vi) four distinct damage states ranging from slight damage to complete damage were considered. The performance thresholds between damage states were estimated from the yield and ultimate displacement capacity (see Table 2) of each SDOF system. Based on the damage thresholds and taking into account the spatial distribution of seismic hazard, the probabilities of exceedance of each damage state were developed.

Table 2 – Damage thresholds of the adopted fragility models [4]

Damage state	Threshold
Slight damage (DS1)	0.75 S_{dy}
Moderate damage (DS2)	0.50 S_{dy}+0.33 S_{du}
Extensive damage (DS3)	0.25 S_{dy}+0.66 S_{du}
Complete damage (DS4)	S_{du}

S_{dy} - Spectral displacement at yield; S_{du} - Spectral displacement at ultimate capacity

6. Damages

The hazard, exposure and vulnerability models, are applied to estimate the expected damages to the buildings located in Thessaloniki and Athens cities, for the Thessaloniki 1978 and the Athens 1999 earthquakes, respectively. Figure 6 shows the distribution of the expected damage states of residential buildings in Athens and Thessaloniki for the scenario damage analysis using the fault rupture models and the USGS Shakemaps. For both Athens and Thessaloniki case studies, irrespectively of the seismic hazard model (rupture model and USGS Shakemap), the damages are in good correlation, with the rupture model leading to slightly higher damages. For the Athens case study, higher damages are found predominantly in the areas, where higher seismic demands are found (Figure 4). The predicted earthquake damages are also compared with the actual damages observed in the study areas after the 1978 Thessaloniki and Athens 1999 earthquakes (Table 3 and Table 4). The results are correlated well with the observed damages, especially for Thessaloniki city using the rupture model (differences about 5%). This was something expected as the Thessaloniki exposure model has less uncertainties (use of 1991 census data in combination with data from previous projects and in-situ work) compared to the Athens exposure model, which is only based on 2011 building census data.

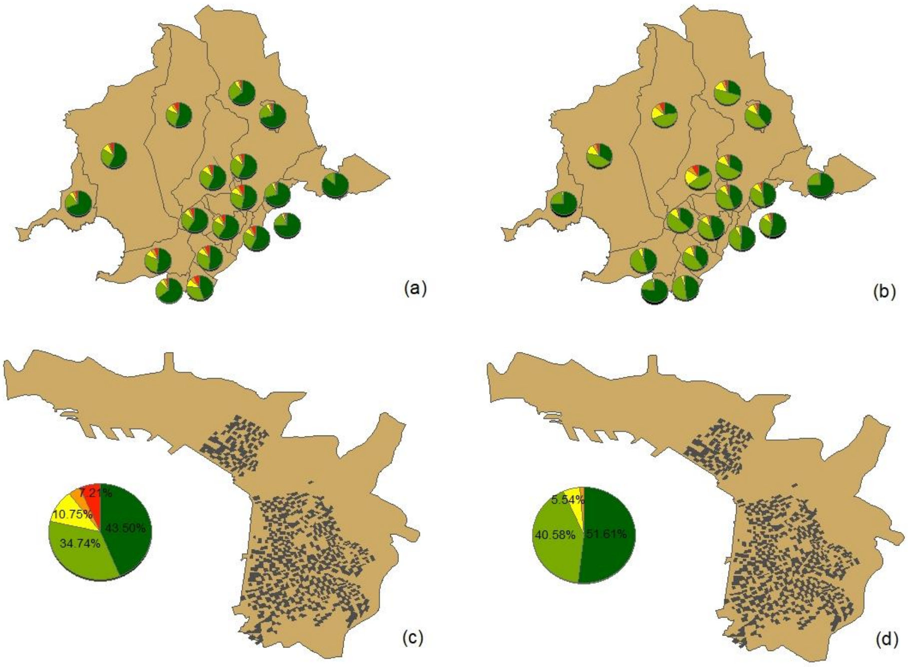

Fig. 6 – Distribution of expected damage states of residential buildings obtained from scenario analysis with OpenQuake for: (a) – (b) Athens 1999 M6.0 earthquake, using the fault rupture model by Roumelioti et al. [7], the Akkar and Bommer GMPE [14] and the USGS $V_{s,30}$ model shown in Figure 2b (a) and the Athens 1999 USGS Shakemap (b), (c) – (d) Thessaloniki 1978 M6.4 earthquake, using the fault rupture model by Roumelioti et al. [13], the Akkar and Bommer GMPE [14] and the USGS $V_{s,30}$ model shown in Figure 2a (c) and the Thessaloniki 1978 USGS Shakemap (d).

Table 3 – Comparison between the estimated (Rupture model and Shakemap) and the actual damages observed in the study area of Thessaloniki after the 1978 earthquake

Damage State	Color tag	Rupture Model	Shakemap	Post-earthquake tagging [21]
No Damage	Green	78.24%	92.2%	74.50%
Slight				
Moderate	Yellow	14.55%	6.95%	19.10%
Extensive				
Complete	Red	7.21%	0.85%	6.40%

Table 4 – Comparison between the estimated (Rupture model and Shakemap) and the actual damages observed in the study area of Athens after the 1999 earthquake

Damage State	Color tag	Rupture Model	Shakemap	Post-earthquake tagging [22]
No Damage	Green	82.83%	83.65%	62.46%
Slight				
Moderate	Yellow	11.16%	13.10%	32.79%
Extensive				
Complete	Red	6.02%	3.25%	4.75%

7. Conclusions

One of the most critical issues in the development of seismic risk assessment tools, especially when applied to large urban areas, is the validation against real earthquake records and observations, which is generally rarely addressed. In the present study, to verify the reliability of the uniform seismic vulnerability, which is under development in Europe under the EU SERA project (http://www.sera-eu.org/en/home/), we compare the damages obtained through the proposed uniform European seismic vulnerability and risk model with the actual earthquake damage observations for two earthquake scenarios.

To this end, the model is applied to estimate the expected damages to the buildings of the central part of Thessaloniki and Athens for the Thessaloniki 1978 and Athens 1999 earthquake scenarios, respectively. For the seismic hazard we used the USGS Shakemaps and the Roumelioti et al. (2003; 2007) fault rupture models [7,13]. For the exposure models we used the building inventories which correspond to the Thessaloniki and Athens building stock situation in 1978 and 1999 respectively. For the vulnerability model we applied the fragility curves by GEM [4]. Estimated damages are compared to the actual damages from the 1978 Thessaloniki and 1999 Athens earthquakes. The results are very promising as we found that despite the numerous uncertainties and the unavoidable simplifications, they are in very good agreement with the reported damages, especially for the Thessaloniki city and in particular when using the whole methodology and the fault rupture model. This challenging work and the good results acquired so far contribute to the efforts towards increasing the resilience of cities.

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