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IMPACT OF MODERATE SIZE EARTHQUAKES THROUGH SKOPJE 2016 AND ZAGREB 2020 CASE STUDIES

Radmila Salic Makreska (1), Katerina Drogreska (2), Cvetan Sinadinovski (3), Zabedin Neziri (4), Ljubco Jovanov (5), Zoran Milutinovic (6), Lazo Pekevski (7), Jasmina Najdovska (8), Dragana Chernih Atanasovska (9), and Daniel Tomic (10)

(1) Assoc. Prof. Dr., Ss. Cyril and Methodius University in Skopje, Institute of Earthquake Engineering and Engineering Seismology (IZIIS) – Skopje, Republic of North Macedonia, r_salic@iziis.ukim.edu.mk

(2) Assist. Prof. Dr., Ss. Cyril and Methodius University in Skopje, Faculty of Natural Sciences and Mathematics, Seismological Observatory – Skopje, Republic of North Macedonia, katerinadrogreska@yahoo.com

(3) Dr., Global SeismiCS - Canberra, Australia, cvetansin@hotmail.com

(4) Ph.D. Student, M.Sc., Ss. Cyril and Methodius University in Skopje, Institute of Earthquake Engineering and Engineering Seismology (IZIIS) – Skopje, Republic of North Macedonia, zabedin@iziis.ukim.edu.mk

(5) Eng., Ss. Cyril and Methodius University in Skopje, Faculty of Natural Sciences and Mathematics, Seismological Observatory – Skopje, Republic of North Macedonia, ljubco.jovanov@hotmail.com

(6) Prof. Dr., Retired, Ss. Cyril and Methodius University in Skopje, Institute of Earthquake Engineering and Engineering Seismology (IZIIS) – Skopje, Republic of North Macedonia,milutin.zvm@gmail.com

(8) Prof. Dr., Retired, Ss. Cyril and Methodius University in Skopje, Faculty of Natural Sciences and Mathematics, Seismological Observatory – Skopje, Republic of North Macedonia, lazo9pekevski@gmail.com

(7) Assist. Prof. Dr., Ss. Cyril and Methodius University in Skopje, Faculty of Natural Sciences and Mathematics, Seismological Observatory – Skopje, Republic of North Macedonia, najdovskaj@yahoo.com

(9) Prof. Dr., Ss. Cyril and Methodius University in Skopje, Faculty of Natural Sciences and Mathematics, Seismological Observatory – Skopje, Republic of North Macedonia, dcernih@gmail.com

(10) Ph.D. Student, M.Sc., Ss. Cyril and Methodius University in Skopje, Institute of Earthquake Engineering and Engineering Seismology (IZIIS) – Skopje, Republic of North Macedonia, danielt@iziis.ukim.edu.mk

Abstract

Even today, moderate earthquakes can cause considerable damage and social disturbance, especially in areas populated with old and masonry buildings. Two recent moderate earthquakes that hit the Balkan peninsula in 2016 and 2020 affected the capital cities of Skopje and Zagreb, respectively. Both have shown the high vulnerability pattern of a current masonry building stock and emphasised the necessity for improvement of existing response, preparedness, and protection measures.

The manuscript analyses, summarizes, and presents the crucial seismo-tectonic aspects and seismological data of both affected cities, then defines P-nodal planes for both strongest earthquake events affecting Skopje 2016 (M_L=5.3) and Zagreb 2020 (M_L=5.5). We analysed and compared macroseismic data, and strong motion records in respect to their amplitude and frequency characteristics and showed the building damage and usability statistics.

The observed differences and similarities that have resulted from this comparative study are to be used further to increase the awareness of the impact of moderate earthquakes, identify gaps and inconsistencies in the coping capacity domain and propose systematic measures to decrease vulnerability of the existing masonry building portfolio.

Keywords: Moderate earthquake, Response measures, Building damage, Skopje, Zagreb

1. Introduction

Earthquakes, especially moderate ones, are frequently experienced natural hazards in the Balkan Peninsula. Non-structural damage patterns characteristic of this type of earthquakes creates enormous panic among residents and building owners/managers. The uncertainty regarding structural stability and building safety becomes an issue related to public (hospitals, schools, kindergartens, etc.), commercial and industrial buildings since the earthquake impact phase dominantly results in disrupted function and evacuation of these buildings. Management of the created panic and safety assurance of the population

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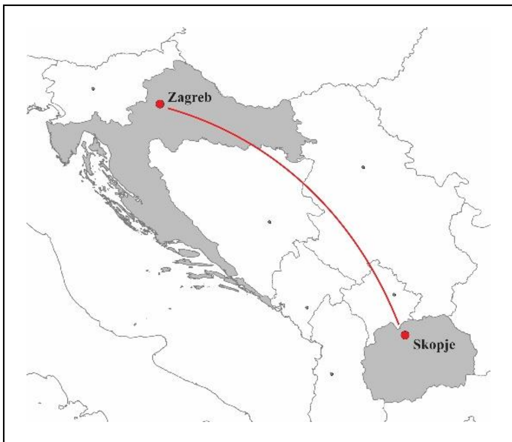
for the purpose of building re-occupation requires rapid building damage and usability assessments (Milutinovic et al., 2018).

The authors were challenged to compare the two recent moderate size earthquakes that hit the Balkan peninsula in 2016 and 2020 and affected the capital cities of Skopje and Zagreb. Both earthquakes have resulted in high vulnerability pattern of a current masonry building stock and emphasised the necessity for improvement of existing response, preparedness, and protection measures. This study provides a general overview comparing the exposure, seismo-tectonic aspects, seismological observations, response measures and procedures as well as discusses in general terms building damage and usability statistics.

2. Exposure

The capital cities of N. Macedonia and Croatia, Skopje and Zagreb, both the largest cities in the country, are representing administrative-political, economic, educational-scientific and cultural centers. Skopje is located in the northern part of the country, in the Skopje valley, along the Vardar River, while Zagreb is placed in the northwestern part of Croatia, along the Sava River and the southern slopes of Medvednica mountain.

The capital cities of Skopje and Zagreb, although recently affected by similar magnitude size earthquakes of M_L5.3 (2016) and M_L5.5 (2020) (https://www.emsc-csem.org/), are also comparable in terms of urban area size (https://en.wikipedia.org/) and number of inhabitants (https://worldpopulationreview.com/) (Figure 1). Moreover, the two cities in the period 1945-1991 were part of the same country (SFR Yugoslavia) in which over those years similar construction typologies were built, the same design standards and construction practices were applied. These similarities widely open the door for a comparative study of the impact of recent moderate size earthquakes on the built environment and population, as well as the implementation of earthquake protection, preparedness and mitigation measures.



City:	Skopje	Zagreb
Urban area (km^2):	571.5	641.0
Altitude (m):	240	158
Population (N°):	567.800 (2016)	684.900 (2020)
Last Earthquake (M_L):	5.3 (11.09.16)	5.5 (22.03.20)


Skopje


Zagreb

Figure. 1. General facts about Skopje and Zagreb Cities

Exposure as one of basic components of seismic risk, according to the UNDRR[1] Terminology (2017) is defined as situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. Accordingly, the most important part of the exposure is the inventory of existing buildings, which overwhelmingly contributes to the social and economic risk (Spence et al., 2012). Systematic collection of exposure data usually is performed in the frame of the official censuses, although the collected attributes most often are very general and not quite reliable for regional risk assessment. Typically, a building inventory usually consists of the following major

[1] UNDRR: United Nations Office for Disaster Risk Reduction

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attributes: location, year of construction, dimensions (height, number of stories, footprint), structural type, dominant construction material (wood, steel, concrete, masonry), lateral force resisting system (bearing wall, shear wall, frame, etc.), occupancy (residential, industrial, critical infrastructure, etc.), number of residents, replacement cost (basis for calculation of economic losses). Once those attributes are collected, a given building is assigned appropriate description code (taxonomy) within a standard classification scheme able to capture average properties among the different building types so that an unambiguous classification is made (Atalić et al., 2019).

According to the summary presented in NERA[2] EC FP7 Project, in relation to the state of knowledge on building inventory data in Europe in the national databases, limited data are available for Skopje and very few about Zagreb (Table 1). Although presented, it must be noted that for N. Macedonia, data related to the lateral load resisting system and exterior walls doesn't exists in the national census database. Also, for N. Macedonia all census 2021 data and statistics related to building inventory are not officially published yet and posted on MAKSTAT database. As of moment, only census 2002 data related to building inventory are available for presentation and analysis. It can generally be concluded that building inventory in both cities is a very poorly defined, and not suitable for reliable risk assessment study.

Table 1. Summary of attributes in national building/dwelling databases, extract (NERA, D.7.2)

Country	Structural System		Building Information			Exterior Attributes				Roof/Floor System		
	Material of Lateral Load Resisting System	Lateral Load Resisting System	Number of Stories	Date of Construction	Occupancy	Building Position within a block	Shape of building plan	Structural Irregularity	Exterior Walls	Roof	Floor	Foundation System
MKD	X	~~X~~	X	X	X	-	-	-	~~X~~	-	-	-
CRO	-	-	-	X	X	-	-	-	-	-	-	-

For general idea, information related to current building stock that has been affected in the recent earthquakes, presented in uniform manner, can be found in the latest published ESRM20[3] exposure model (Crowley et al., 2021) for residential, commercial, and industrial buildings. For the purpose of this study, building inventory has been extracted related to the wider cities area on NUTS[4]3 level i.e., Skopje region that comprises of 17 both urban and rural municipalities (Aerodrom, Butel, Gazi Baba, Gjorche Petrov, Karposh, Kisela Voda, Saraj, Centar, Chair, Shuto Orizari, Arachinovo, Zelenikovo, Ilinden, Petrovets, Sopishte, Studenichani and Chucher – Sandevo) and Zagreb that comprises of City of Zagreb and Zagreb County (Table 2). What can be observed is that in both cities and surrounding area around 80% of the building stock (Skopje 82.73% and Zagreb 80.10%) belongs dominantly to 3 building typologies (marked with yellow in the table) i.e., (1) Concrete frame with infill panels, low rise, low/moderate code, (2) Confined or reinforced masonry, low rise and (3) Unreinforced masonry, low rise; according GEM[5] Building Taxonomy v3.1 (Silva et al., 2021). Also, it is notable that, the masonry building typologies in total dominates over others (Skopje 54% and Zagreb 71%), out of which for the Zagreb case it is obvious prevalence of the unreinforced masonry low rise typology with approximately 38% of total stock.

[2] NERA: Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation
[3] ESRM20: European Seismic Risk Model
[4] NUTS: Nomenclature of territorial units for statistics - Eurostat
[5] GEM: Global Earthquake Model

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Table 2. ESRM20 Exposure model, extract (Crowley et al., 2021)

MACRO__ TAXONOMY	SKOPJE REGION					GRAD ZAGREB & ZAGREB COUNTY				
	RES	**COM**	**IND**	**Total**	**%**	**RES**	**COM**	**IND**	**Total**	**%**
Concrete frame with infill panels, low rise, low/moderate code	36695	2574	0	39269	**29.86**	50346	784	408	51538	**13.83**
Concrete frame with infill panels, low rise, pre code	8017	1215	614	9846	**7.49**	0	135	0	135	**0.04**
Concrete frame with infill panels, midrise, low/moderate code	1469	594	154	2217	**1.69**	43895	730	0	44625	**11.98**
Concrete frame with infill panels, midrise, pre code	948	491	0	1439	**1.09**	2516	870	0	3386	**0.91**
Concrete frame, low rise	0	0	307	307	**0.23**	0	0	2925	2925	**0.79**
Concrete frame, low rise, low/moderate code	0	0	338	338	**0.26**	0	0	476	476	**0.13**
Concrete frame, low rise, pre code	0	0	338	338	**0.26**	0	0	0	0	**0.00**
Concrete frame, mid rise	0	0	61	61	**0.05**	0	0	0	0	**0.00**
Concrete frame, midrise, low/moderate code	0	0	61	61	**0.05**	0	0	0	0	**0.00**
Concrete wall, low rise	0	985	0	985	**0.75**	0	0	0	0	**0.00**
Concrete wall, low rise, low/moderate code	0	673	0	673	**0.51**	0	0	952	952	**0.26**
Concrete wall, low rise, pre code	0	312	0	312	**0.24**	0	0	0	0	**0.00**
Concrete wall, midrise, low/moderate code	833	698	0	1531	**1.16**	448	113	0	561	**0.15**
Concrete wall, midrise, pre code	0	328	0	328	**0.25**	0	0	0	0	**0.00**
Confined or reinforced masonry, low rise	34898	3988	399	39285	**29.87**	102160	758	272	103190	**27.70**
Confined or reinforced masonry, mid rise	807	888	0	1695	**1.29**	11468	154	0	11622	**3.12**
Steel, low rise	0	1649	614	2263	**1.72**	0	0	1088	1088	**0.29**
Steel, mid rise	0	0	123	123	**0.09**	0	0	612	612	**0.16**
Unreinforced masonry, low rise	30179	0	61	30240	**23.00**	142070	1542	68	143680	**38.57**
Unreinforced masonry, mid rise	188	0	0	188	**0.14**	7675	96	0	7771	**2.09**
Total:	114034	14395	3070	**131499**	100.00	360578	5182	6801	**372561**	100.00

3. Seismo-tectonic aspects

3.1. Geology and seismotectonics

The territory of the Balkan Peninsula (Figure 2) is characterized by active geodynamics, controlled by the active tectonic processes in the Eastern Mediterranean. Nowadays, the Balkan Peninsula is in a collision zone between three major plates: Eurasian, African, and Arabian. The active tectonic processes in the Eastern Mediterranean are most influenced by the: (1) subduction of the Adriatic microplate under the Dinarides; (2) subduction of the Ionian and Levant micro plains under the Hellenic trench; and (3) the collision between the Eurasian and the Arabian plates, related to the North Anatolian fault zone (NAFZ). (Dumurdzanov et al. 2005; Burchfiel et al., 2006). Due to this complex tectonic setting, the

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Balkan Peninsula is one of the most seismically active regions in the Eastern Mediterranean, where strong and damaging earthquakes are quite frequent.

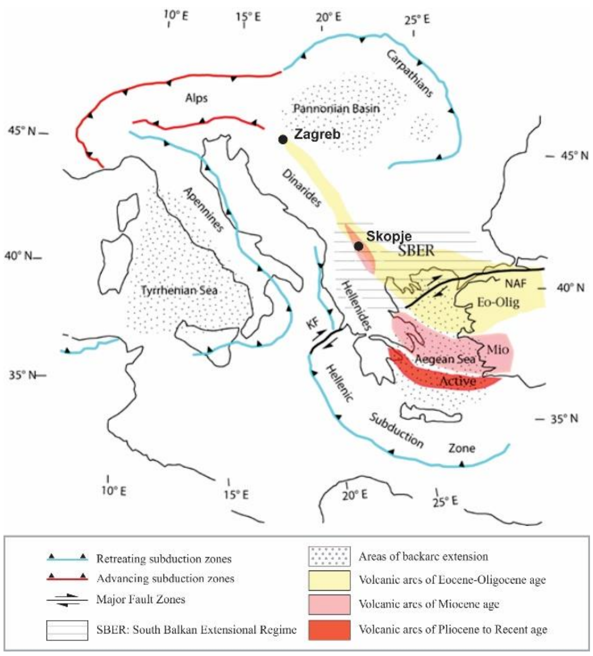

Figure 2. Simplified tectonic map of Eastern Mediterranean region (Dumurdzanov et al., 2005)

The capital of N. Macedonia, Skopje is located in the Skopje valley closely related to the contemporary tectonic activity of the valley, a young tectonic depression, intersected by many neotectonic faults. On the other side, Zagreb is located in a contact zone of the Alps, the Dinarides and the Western regions of the Pannonian Basin, with complex tectonic and structural relationships (Markušić, 2008), as a result of the interaction of the upper crustal tectonic blocks formed during the Mesozoic to Cenozoic evolution of the area (Van Gelder et al., 2015). Seismicity of both epicentral areas where the capitals are located, is due to different tectonic processes, with frequent occurrence of weak to strong earthquakes. In Skopje epicentral area, the subduction of the Skopje valley and the differential vertical and horizontal displacements of the surrounding mountains, are expressed in the regional tectonic compression with the activation of the mostly active Skopje – Kjustendil and Skopje – Crna Gora faults (Fig. 3a).

The Zagreb area belongs to the epicenter area Medvednica Mountains. This is a part of the contact area of three major regional tectonic units: the Alps in the northwest, the Pannonian Basin in the east and the Dinarides in the south. The causes of earthquakes are tectonic movements that occur in the upper crust because of interactions between the underlying lithospheric plates: the European plate and the Adriatic microplate. As a result of the compression and/or subduction of the plates, the upper crustal faults become seismic sources of earthquakes. The earthquakes in the area are the result of the interface between crustal fragments bordered by active faults (Markušić at al., 2020), (Fig. 3b).

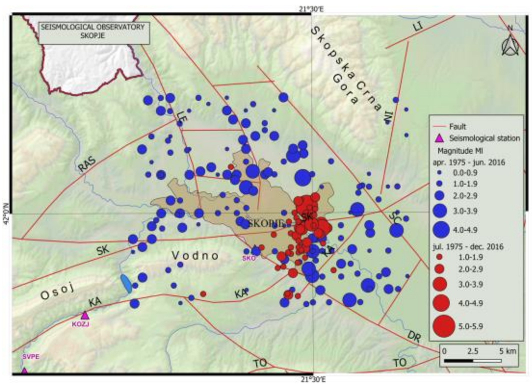

Figure 3a. Seismotectonic map of the Skopje area (SO-PMF[6], Skopje)

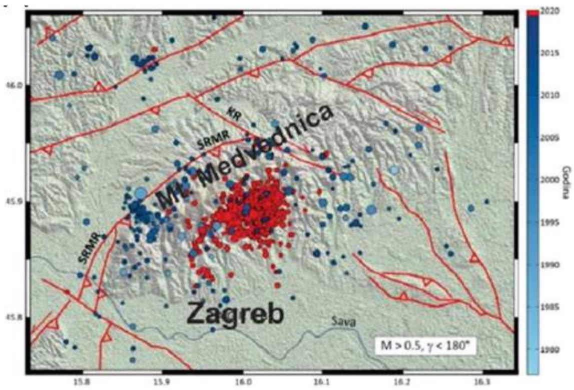

Figure 3b. Seismotectonic map of the Zagreb area (Atalić et al., 2021)

Figure 3. Seismotectonic maps of Skopje and Zagreb wider area

[6] SO-PMF: Seismological Observatory, Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University in Skopje

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3.2. Seismicity

Both considered regions are characterized by pronounced seismic activity. The historic evidence shows that Skopje epicentral area has been destroyed by strong earthquakes in 518, 1555 and 1963 (Jordanovski et al., 1998; Milutinovic et al., 1998), while the Medvednica Mountains epicentral area experienced strong earthquakes in 1830, 1838 and 1880, the great Zagreb earthquake (Kozák and Čermák, 2010). Besides from local earthquakes, those areas have suffered several times from earthquakes that occurred in the wider area like the impact of Gnjilane earthquake (1921) (Jancevski, 1987) in South Serbia on Skopje, Ljubljana earthquake in 1978 (Kozák and Čermák, 2010) and Petrinja earthquake in 2020 on Zagreb (Markusic et al,. 2021). As the evidence shows, both areas have a rich seismic history which continues even today, as a result of the constant activity of the normal strike-slip Skopje – Kjustendil fault (SK, Fig.3a) (striking approximately E-W, dipping NNE) and Skopje – Crna Gora fault (SC, Fig.3a) (striking approximately N-S, dipping WSW) for the Skopje epicentral area (Jordanovski et al., 1998; Milutinovic et al., 1998), and the reverse northern edge of Medvednica fault (striking approximately NE-SW, dipping SE) (SRMR on Fig.3b) and nearly perpendicular normal strike-slip Kasina fault (KR on Fig.3b) (Van Gelder et al., 2015) for the Medvednica Mountains epicentral area (Tomljenovic, 2002). The predominant hypocentral depth of the located earthquakes in the Skopje area is ranging between 0.1 and 10 km (Sinadinovski et al., 2021) and pretty similar, for the Medvednica Mountain area ranges between 3 and 10 km (Markušić, 2008), which makes the granite layer of the crust active, while the lower part of the crust is almost aseismic.

3.3. Seismic hazard

Estimation of probabilistic seismic hazard for both Skopje and Zagreb cities in relation to referent EC8[7] return periods (95 and 475 years) are comparable. The latest national (EC8 maps; Milutinovic et al., 2016, Herak et al., 2011), regional (BSHAP; Gulerce et al., 2017), and European studies (ESHM20; Danciu et al., 2021) have shown that the values are ranging between 0.20-0.25g for Skopje and 0.20-0.26g for Zagreb for RP475 and 0.07-0.10g for Skopje and 0.08-0.13g for Zagreb in relation to RP95 (Table 3). Seismic hazard values used as referent in the design practice (EC8) are also very similar (Table 3, Figure 4) which implies a design of regular buildings with similar strength characteristics.

Table 3. Seismic hazard values for EC8 referent return periods (Soil type A)

	RP95		RP475	
	SK	ZG	SK	ZG
BSHAP2	0.10	0.08	0.20	0.20
ESHM20	0.07	0.09	0.20	0.24
NA/EC8	0.10	0.13 *(0.12-0.14)*	0.25	0.25 *(0.24-0.26)*

Figure 4a. N. Macedonia, extract (MKC EN 1998-1/NA:2020)

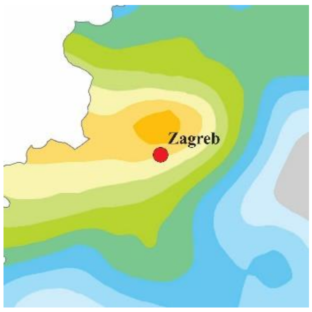

Figure 4b. Croatia, extract (HRN EN 1998-1/NA:2011)

Figure 4. Seismic hazard maps for RP475 related to EC8 National Annexes

4. Seismological observations

4.1. Comparison of M_L5.3 2016 Skopje and M_L5.5 Zagreb 2020 earthquake's parameters

On 11 September 2016 at 13:10 UTC a moderate size earthquake M_L5.3, with a focal depth of approximately 10km occurred near the N. Macedonian capital, Skopje. Using the data from the Macedonian Seismological Network (MA), the epicentre was located at 42.008°N and 21.488°E,

[7] EC8: Eurocode 8

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approximately 5km from the downtown area. The mainshock caused significant macroseismic effects and was felt in the city area with a maximum intensity of VII degrees EMS-98 scale (Fig 5a), making it the strongest earthquake that hit Skopje in the last 59 years.

An earthquake with a similar magnitude of M_L5.5 with a focal depth of 10km was registered on 22 March 2020 at 05:24 UTC in Zagreb. Using the data from the Croatian national seismological network (CR), the epicentre was located at 45.907°N and 15.970°E about 7 km north of the downtown area, in the Markuševec and Chučerje neighbourhoods. The mainshock caused significant macroseismic effects and was felt in the city area with a maximum intensity of also about VII degrees EMS-98 scale (Fig 6a) (Markušić et al., 2020). This is the strongest earthquake recorded in the last 140 years in the area of Zagreb.

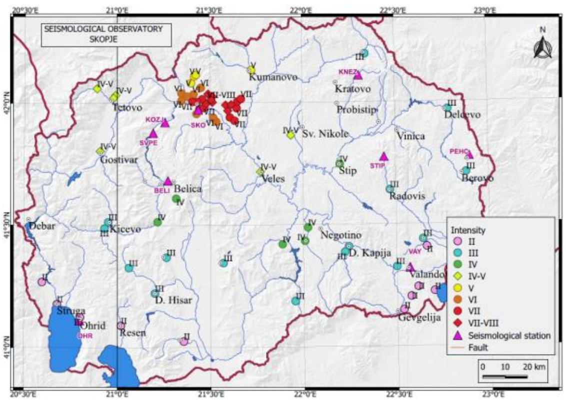

Figure 5a. Intensity map of the 11 September 2016 M_L5.3 Skopje earthquake (SO-Skopje)

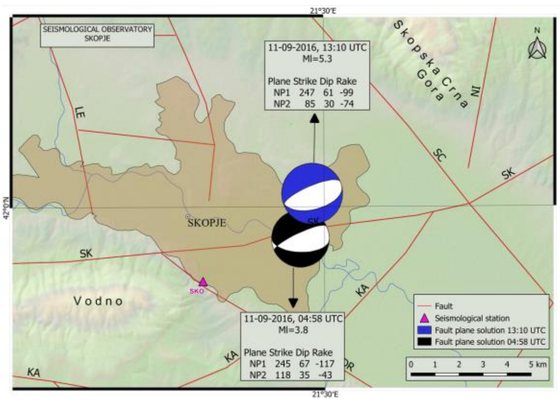

Figure 5b. Fault plane solution of the 11 September 2016 Skopje earthquake, blue for the main shock, black for the foreshock (SO-Skopje)

Figure 5. Skopje earthquake, intensity and FPS maps

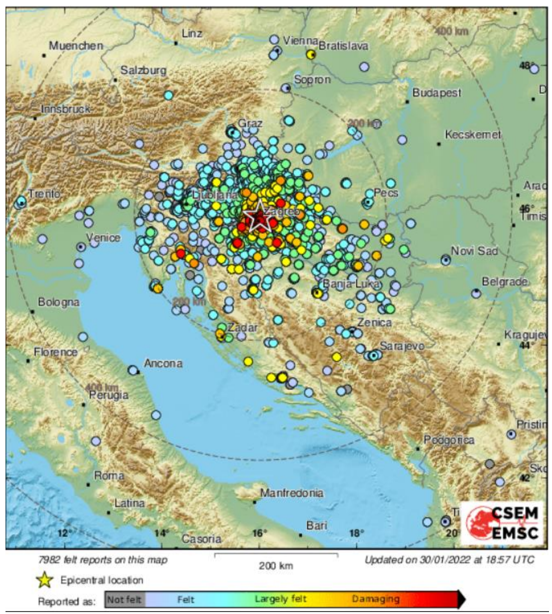

Figure 6a. Intensity map for Zagreb earthquake (EMSC)

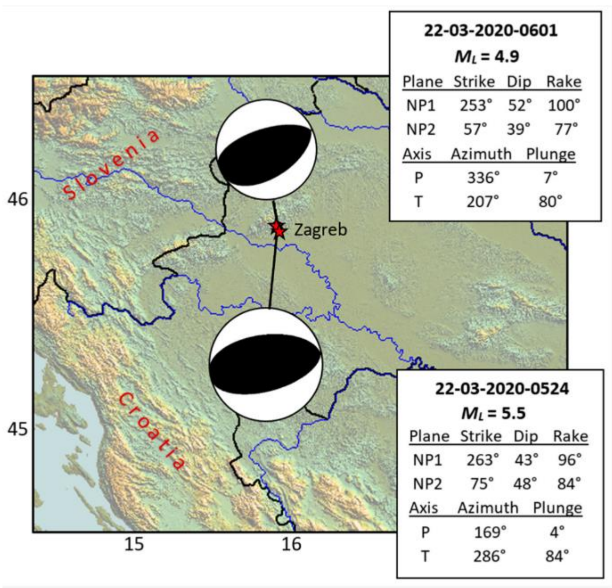

Figure 6b. Fault plane solution for the Zagreb 2020 main earthquake and the strongest aftershock (Markušić et al., 2020)

Figure 6. Zagreb earthquake, intensity and FPS maps

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Both events were followed by an aftershock sequence, while the Skopje earthquake had one significant foreshock earlier the same day. The source mechanisms for the main shocks (11.9.2016, 13:10 UTC, M_L5.3 – Skopje; 22.3.2020, 05:24 UTC, M_L5.5 – Zagreb), the strongest foreshock (11.9.2016, 04:58 UTC, M_L3.8 – Skopje) and the strongest aftershock (22.03.2020, 06:01 UTC, M_L4.9 – Zagreb) of the earthquake sequences were calculated using the most prominent method using the polarities of the first P seismic motions (Fig. 5b and 6b). The source mechanism's parameters confirm that Skopje's mainshock is a normal right lateral faulting, striking toward WSW, dipping toward NNW, corresponding to a block of regional Skopje – Kjustendil fault - contact between the uplifting Skopje-Crna Gora and Vodno blocks and the Skopje depression. The source mechanisms for Zagreb's sequence define both events as reverse right lateral faulting, striking toward WSW, dipping toward NNW. According to the mechanism parameters, these faultings are associated with the Medvednica fault (Markušić et al., 2020).

4.2. Strong motion and spectral analysis

Two representative strong motion records from both Skopje and Zagreb earthquakes are selected for comparative purposes only, presented in detail in Sinadinovski et al. (2022).

The records from the station in N. Macedonia coded as SKO (Skopje, Seismological Observatory) equipped with EpiSensor Kinemetrics instrument, a maximum acceleration for the Skopje mainshock was detected on the Z-component with a measured zero-to-peak value of 555,000 counts or peak ground acceleration (PGA) of 0.140 g (Fig. 7a). Similarly, the records from the station in Croatia coded as QUHS equipped with Güralp T5GD1 instrument with a general set of response curves to convert the measurements from counts into units of acceleration, a maximum acceleration for the Zagreb mainshock shows the vertical Z component with a value of 0.225g (Fig. 7b), even though the horizontal components carried most of the energy in their respective S-waves (Sinadinovski et al., 2022).

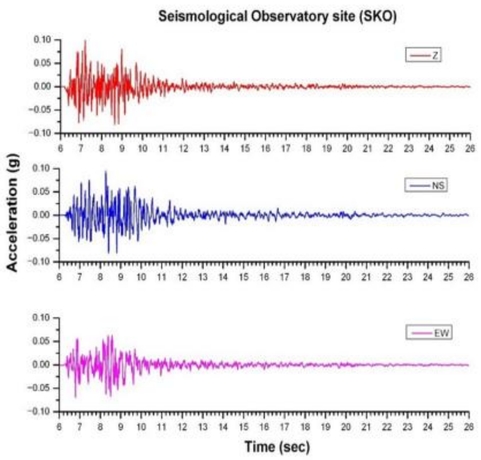

Figure 7a. Skopje Earthquake M_L5.3, Station SKO

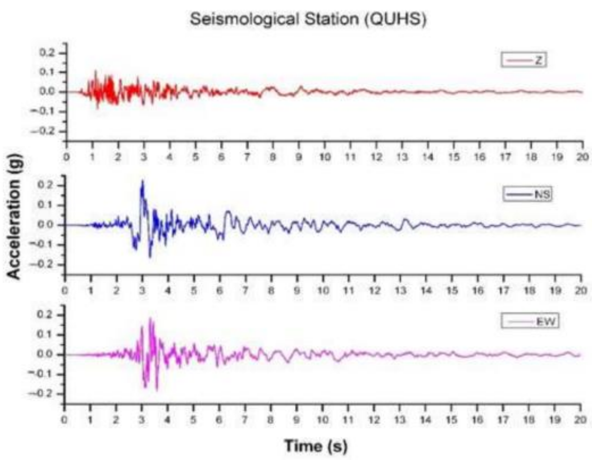

Figure 7b. Zagreb Earthquake M_L5.5, Station QUHS

Figure 7. Acceleration records (Sinadinovski et al., 2022)

A response spectra analysis for the selected earthquakes were performed on the whole record length in raw format over various natural periods. Although the range of main interest for structural engineers is between 0 to 4 s, a response acceleration spectrum (in g) for 5% damping, with a period up to 10s was performed to order to detect any anomalies due to resonance effects, polarization, or surface waves reflection of the sub-layers (Fig 8) (Sinadinovski et al., 2022).

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The maximum spectral peaks for the SKO records were at 0.2 s on all of the three components, while secondary peaks were concentrated between 0.06 and 0.1 s, equivalent to a frequency of 5–16 Hz. The dominant frequencies of 5 Hz or 0.2 s found on the SKO record of the instrument installed on bedrock (ground type A, according to Eurocode 8), and the top layers velocities using the Balkan model (Jancevski, 1987), lead to an estimated value of 0.9 V_S velocity which is a general rate for rupture propagation on faults. The spectral peaks for the QUHS station are mainly between 0.1 and 0.2 s, equivalent to a frequency of 5–10 Hz, with the horizontal components having an additional peak at around 0.5 s or 2 Hz. According to geological maps, QUHS station is located in an area with alluvial deposits (ground type C, according to Eurocode 8). In Table 4, represented are observed and computed parameters for the selected events (Sinadinovski et al., 2022).

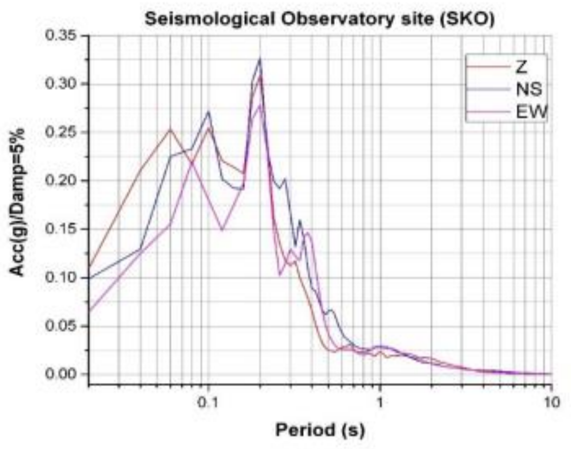

Figure 8a. Skopje 2016 M_L5.3 earthquake at the seismological station SKO

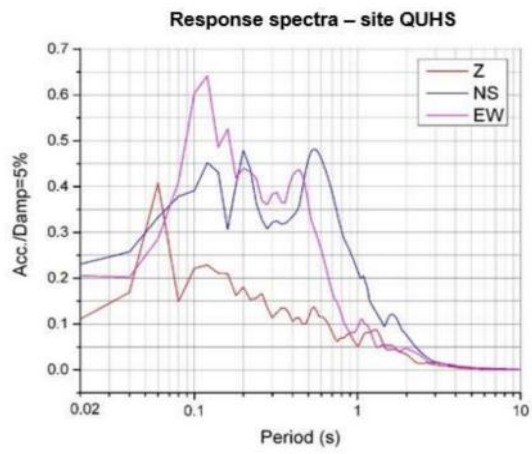

Figure 8b. Zagreb 2020 M_L5.5 earthquake at the seismological station QUHS

Figure 8. Three component response spectra (Sinadinovski et al., 2022)

Table 4. Observed and computed parameters for the selected events

	Hypocentral Distance (km)	PGA (g)	PGV (cm/s)	Sa (5%) (g)	Period Range
Skopje 2016	12.3	0.140	4.3	0.325	0.2
Zagreb 2020	12.5	0.225	7.2	0.4-0.65	0.1-0.2

5. Response measures and procedures

Being hit by an earthquake, although moderate size, both capitals and mandated institutions were challenged to enforce rapid response measures with an aim to help the eventually injured residents, manage panic and fear as well as rapidly screen the damage situation.

5.1. Immediate response measures

Right after the occurrence of the main shock in the afternoon hours on Sunday, September 11, 2016, the Managing Committee of the Crisis Management Centre (CMC) in Skopje, called an urgent meeting with the representatives of all institutions mandated by crisis management i.e. representatives of the Ministries for: internal affairs, external affairs, health, economy, environment and spatial planning, then representatives of the Republic President Office, Seismological Observatory (SO-PMF/UKIM), Institute of Earthquake Engineering and Engineering Seismology (UKIM-IZIIS), Health Centre – Skopje and University Clinics in Skopje. On the first Committee session, since there were no reported victims or injured, was decided that of the primary importance is performing fast safety and usability assessment of the buildings, with priority on buildings that are of public and special interest (hospitals,

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schools, kindergartens etc.) for which the users reported certain mode of damage. This fast assessment was agreed to be performed by the expert teams form UKIM-IZIIS. For the purpose of declaring damages, the CMC dedicated a special telephone line and e-mail (Milutinovic et al., 2018). Quite enormous panic among the residents and occupants was created due to the main shock. Despite the negligible earthquake effects on the built environment, the created panic was also result of the remaining memory of the devastating Skopje Earthquake from July 1963. Panic was successfully managed with frequent media statements as well as frequent on-site visits and interactions with the local residents from various experts and representatives from mandated institutions.

The March 2020 Zagreb earthquake occurred in the specific conditions of beginning of Covid-19 pandemic. It was a period when the pandemic measures, likewise in most of the European countries, were extremely strict. A number of employees were advised to take annual leave and left Zagreb just before the earthquake happened. Zagreb was much deserted on that early Sunday morning, a fortunate circumstance given the aftermath of the earthquake. Immediately after the main shock, the Civil protection services were activated for emergency action. The members of the Zagreb EMO, the Directorate of Civil Protection of the Ministry of the Interior and of the Zagreb Faculty of Civil Engineering convened establishing the Crisis headquarters for operational management at the EMO. Fire and communal services together with units of the Croatian army were called upon to maintain order and start clearing the city center and surrounding streets. made Fortunately, the earthquake did not cause any major collapse of buildings or transportation facilities that would fully occupy the emergency services. The focus was therefore put on the assessment of damage and safety of affected buildings and infrastructure. Since there was no previously established inspection plan at city level, the technical experts self-organized using their experience and previous collaborations and under the guidance of experts from the Faculty of Civil Engineering (Atalić et al., 2021). As the scale of the destruction was unknown in the first hours all engineers who had undergone exercises and training for post-earthquake inspection of buildings were called upon by private calls. One of the first actions was to send them to lead the inspection of hospital buildings in the historic downtown, already identified as critical for post-earthquake recovery (Šavor Novak et al. 2019). A public call line was made available for all the civil engineers, on the first day after the main shock, to help and assist in the preliminary assessment of damaged buildings, by contacting first the Directorate. The total number of volunteer engineers was about 500 (Stepinac et al., 2021).

5.2. Earthquake damage and usability assessment procedures

Yugoslavia has a long experience in administratively institutionalized damage assessment. The first Guidelines on the "Unique methodology for estimation of losses from elementary disasters", based on Federal agreement for evaluation and assessment of losses from elementary disasters (OGoSFRY No. 24/78 of 5 May 1978) was enforced in 1979 (OGoSFRY No. 17/79 of 21 April 1979), being revised in 1987 (OGoSFRY No. 27/87 of 10 April 1987) and in Macedonia again in 2001 (OGoRM No. 75/01 of 19 September 2001) and 2021 (OGoRNM No. 181/21 of 5 August 2021).

5.2.1. Assessment procedure used after 2016 Skopje earthquake

The inspection of the building stock after 2016 Skopje earthquake does not include standard damage assessment procedure defined by Unique Methodology (OGoRM No. 75/01 of 19 September 2001) but fast (rapid) assessment of building stability and usability, since it was estimated that the effect of the earthquake on the build environment is negligible. Damage and usability classification was done according to the UKIM-IZIIS methodology which classifies buildings into three (3) damage states, five (5) damage degrees and three (3) usability categories. All received requests for inspection through CMC concerning buildings from public and special interest were send to the managing body in UKIM-IZIIS, and all the others (dominantly residential buildings) were sent to the managing bodies in the appropriate Skopje City Municipalities. The buildings that were inspected by Municipality teams and diagnosed as

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buildings with possible stability issues were sent to UKIM-IZIIS for second assessment (Milutinovic et al., 2018) (Figure 9).

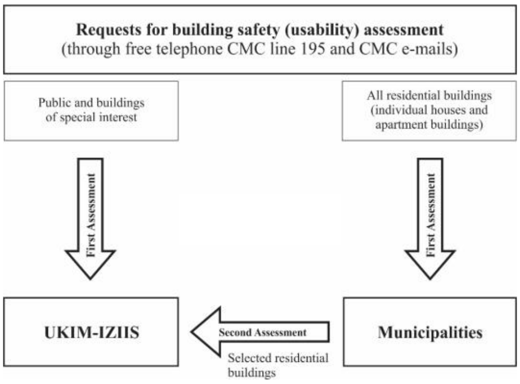


Figure 9. Requests for usability and safety assessment process flow chart

The overall assessment was performed in the period September 11 – October 31, 2016. The inspection of the majority of the building stock (84.8%) was realized during the month of September 2016.

It has to be stated also that, the teams of UKIM-IZIIS inspect the bridges located on the main roads in Skopje and its vicinity for any potential damage. Further on, some industrial buildings were also checked on the demand of their management.

5.2.2. Assessment procedure used after 2020 Zagreb earthquake

Immediately after Zagreb earthquake, at the EMO headquarters was initiated the fine adjustment of the initial safety and usability assessment methodology. Promptly, a general call was sent for mobilization of all engineers with expertise in the (1991–1995) post-war reconstruction or with knowledge related to traditional masonry structures. Programming of a mobile application (Collector for ArcGIS) for acquisition of field observations was initiated at the end of the first day; it was then tested the next day and put into operation a day later. The form was created according to the Italian (Baggio et al. 2007) and Greek (Anagnostopoulos et al. 2004) experience taking into account local building features and observed characteristic damage to gable walls, roofs and chimneys. The form is firstly considered for the assessment of masonry and reinforced concrete buildings, but it can be also used for other building types (Uros et al., 2020). All data was stored in a GIS based database for efficient information flow in both directions. (Atalić et al., 2021). Used methodology classifies buildings into three (3) usability categories and six (6) usability subcategories.

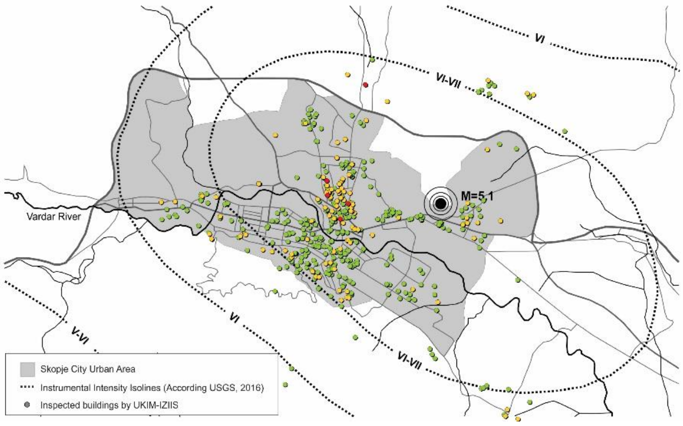
The work on post-earthquake damage inspection and assessment was coordinated by the Ministry of Construction and Physical Planning in cooperation with numerous partners from the government and the industry. The inspection of residential buildings was conducted visually and was more detailed in case of older masonry buildings and buildings that suffered apparent structural damage. Decisions on the short-term usability were made in discussion between the team members based on the current damage state and considering potential behaviour of the structure in case a stronger shaking should have occurred during the still ongoing aftershock sequence. Decisions on usability of critical infrastructure (e.g., bridges) and of essential facilities (e.g., hospitals, schools) were made in agreement with the headquarters and people responsible for the institution. In both cases, the engineering experience and intuition were decisive for the evaluation of the safety and accessibility (Atalić et al., 2021).

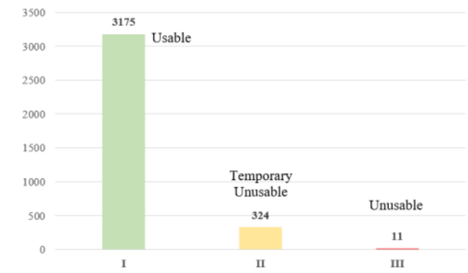
The post-earthquake field inspections of damage incurred to buildings were carried out until June 30th, 2020, when the inspections were officially finished.

6. Building damage and usability statistics

After 2016 Skopje earthquake, through CMC channels were obtained in total 2,885 requests for usability and safety assessment, out of which 625 (Figure 9) were assessed by UKIM-IZIIS. The biggest concentration of all inspected buildings was related to four (4) Municipalities: Chair, Centre, Gazi Baba and Kisela Voda as it was expected since those Municipalities contains considerable number of masonry, pre 1963 and sub-standard buildings. Also, those Municipalities were found to be very near to the epicentre of the main shock. According to Usability Classification (UC), 94.19% of the inspected buildings are classified as usable i.e., with slight non-structural damage, very isolated or negligible structural damage, 5.61% as temporary unusable i.e., with extensive non-structural damage, considerable structural damage but yet repairable structural system and 0.20% unusable i.e., destroyed, partially or totally collapsed structural system (Milutinovic et al., 2018) (Figure 10a).

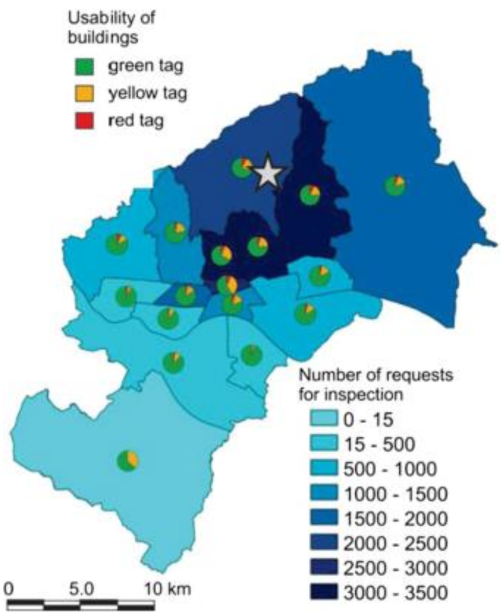
In parallel after 2020 Zagreb earthquake, in total, more than 25,500 building inspections were performed or about 19.6% of the approximately 130,000 buildings within the city limits. Overall, about 75% of all inspected buildings were green tagged (U1 and U2), 20% temporarily unusable (PN1 and PN2) and 5% unusable (N1 and N2). It may be observed that the highest concentration of inspected buildings and at the same time of the unusable buildings is located in the central city area and in districts close to the epicentre (Atalić et al., 2021; Stepinac et al., 2021) (Figure 10b).

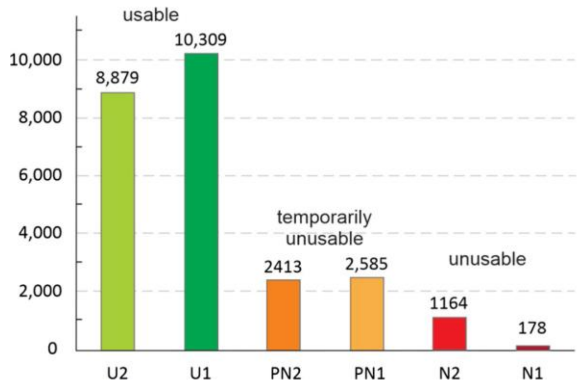




UC	I	II	III
% INS IZIIS	73.17	25.91	0.91
% INS TOT	94.19	5.61	0.20

a) Disposition of inspected buildings in Skopje (according to Milutinovic et al., 2018)





UC	I	II	III
% INS	75.16	19.58	5.26

b) Disposition of inspected buildings in Zagreb (according to Atalić et. al., 2021)

Figure 11. Disposition of the inspected buildings by Usability Category (UC)
(● Usable [I] ● Temporary Unusable [II] ● Unusable [III])

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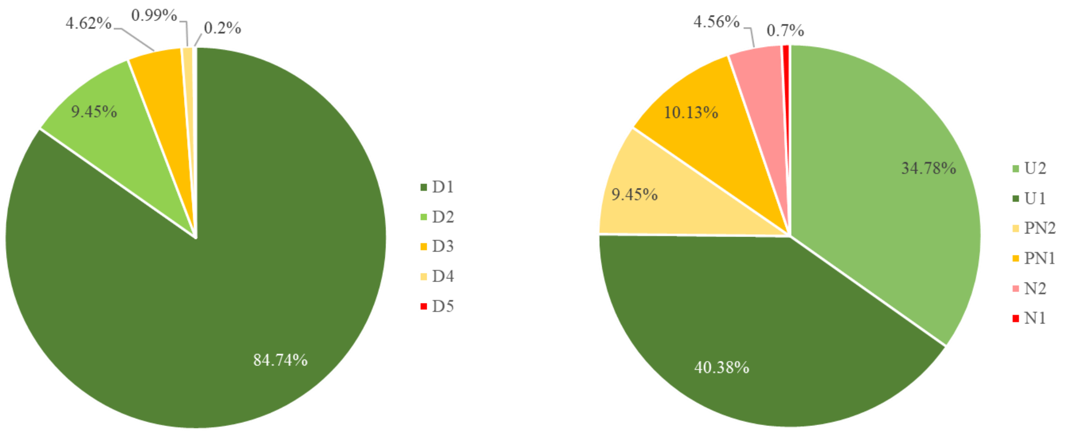
In relation to 2016 Skopje earthquake, Milutinovic et al. (2018) stated that the concentration of the reported damages was found to be in the masonry type structures, buildings constructed before 1964, dominantly residential buildings and low to medium rise story buildings. Similarly, inspection results after 2020 Zagreb earthquake according to Atalić et al. (2021) suggest that nearly all of the damage occurred in older masonry housing units and heritage buildings not designed to resist lateral dynamic loads. About one third of all buildings in Zagreb were built before 1964, when the first Seismic Construction Code was introduced. The vast majority of buildings built afterwards did not suffer any apparent impacts during the earthquake.

If compared the number of inspected buildings classified under the usability category II (Temporary Unusable) together with III (Unusable) in relation to the total number of buildings in the city affected region, can be concluded that very negligible number of buildings in Skopje were affected (0.12%) and much larger number in Zagreb (1.70% if considered ESRM20 data or 4.87% if considered building stock count in Atalić et al., 2021) (Table 5). Taking aside the other parameters, most probably the obvious difference in damage degree distribution (Figure 11) is due to the fact that Zagreb building stock contains larger amount of masonry structures compared to Skopje, which is also evident from ESRM20 exposure model (Table 2), especially in the group of unreinforced masonry, low rise buildings.

Table 5. Usability of inspected buildings in relation to the current exposure

Skopje	Buildings/No		Usable		Temporary Unusable		Unusable	
			D1	D2	D3	D4	D5	-
	Inspected	2,885	2445	273	133	28	6	-
			84.74%	9.45%	4.62%	0.99%	0.20%	-
			94.19%		5.61%		0.20%	
	ESRM20	131,499	1.86%	0.21%	0.10%	0.02%	0.00%	-
			2.07%		0.12%		0.00%	
Zagreb	Buildings/No		Usable		Temporary Unusable		Unusable	
			U2	U1	PN2	PN1	N2	N1
	Inspected	25,528	8879	10309	2413	2585	1164	178
			34.78%	40.38%	9.45%	10.13%	4.56%	0.70%
			75.16%		19.58%		5.26%	
	ESRM20	372,561	2.38%	2.77%	0.65%	0.69%	0.31%	0.05%
			5.15%		1.34%		0.36%	
	Atalić et al., 2021	130,000	6.83%	7.93%	1.86%	1.99%	0.90%	0.14%
			14.76%		3.84%		1.03%	



a) Skopje b) Zagreb

Figure 11. Damage and usability degree in respect to inspected buildings

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7. Conclusions

Moderate size earthquakes are quite a frequent hazard in the Balkan Peninsula. Even today they can cause significant material losses and disruption to basic and vital services, due to the fact that in the Balkan countries still prevails masonry type buildings, dominantly built before 1964. This fact was confirmed by the impact of the last two moderate size earthquakes that hit Skopje and Zagreb in 2016 and 2020.

The latest developed exposure model for Europe (Crowley et al., 2021) accounting for residential, commercial, and industrial buildings, shows that masonry building typologies in total dominates over others for Skopje 54% and Zagreb 71%, out of which for the Zagreb case it is obvious prevalence of the unreinforced masonry low rise typology with approximately 38% of total stock.

The complex geotectonic setting of both Skopje and Zagreb cities conditions relatively high seismic hazard values ranging between 0.20-0.25g for Skopje and 0.20-0.26g for Zagreb (RP475) and 0.07-0.10g for Skopje and 0.08-0.13g for Zagreb (RP95), according the latest national, regional and European studies (Milutinovic et al., 2016; Herak et al., 2011; BSHAP - Gulerce et al., 2017; ESHM20 - Danciu et al., 2021). Those values are also in line with the historical seismicity data, according to which Skopje and Zagreb in the past has also experienced moderate to strong damaging earthquakes.

Although similar in magnitude size, hypocentral depth and macroseismic intensity, the focal mechanisms of 2016 Skopje and 2020 Zagreb earthquakes significantly differs, i.e., normal right lateral faulting in Skopje and reverse right lateral faulting in Zagreb.

Two strong motion records were selected for comparison purposes, obtained from SKO (Skopje, Soil type A) and QUHS (Zagreb, Soil Type C) stations, on relatively equal distances from the epicenter. The maximum spectral peaks for the SKO records were at 0.2 s on all of the three components, while secondary peaks were concentrated between 0.06 and 0.1 s, equivalent to a frequency of 5–16 Hz. The spectral peaks for QUHS station are mainly between 0.1 and 0.2 s, equivalent to a frequency of 5–10 Hz, with the horizontal components having an auxiliary peak at around 0.5 s or 2 Hz. SKO station has recorder maxPGA of 0.14g and QUHS station 0.22g (Sinadinovski et al., 2022).

Despite Yugoslavian long experience in administratively institutionalized damage assessment, the last 2 earthquakes were “surprise” to the relevant authorities in both countries, which clearly shows the need of urgent system preparedness measures and improvement of current procedures and legislations, as well as implementation of the latest smart technologies and GIS developments.

Effective and very fast damage assessment comes out as a necessity in both cases. Rapid procedures were used, for Skopje modified UKIM-IZIIS methodology, and for Zagreb methodology adopted from Baggio et al. (2007) and Anagnostopoulos et al. (2004), modified to account for the local building features and observed characteristic damage to gable walls, roofs and chimneys. Both methodologies used have classified the buildings in three usability categories: usable, temporary unusable and unusable.

After Skopje earthquake inspected were 2,885 buildings for the period of app 50 days, and 25,528 for the period of app 100 days after Zagreb earthquake. In relation to both earthquakes, the concentration of the reported damages was found to be in the masonry type structures, buildings constructed before 1964, dominantly residential and heritage buildings and low to medium rise story buildings. Comparing to current building exposure (ESRM20), out of function (temporary unusable and unusable) buildings for Skopje were reported 0.12% and much larger number in Zagreb (1.70% if considered ESRM20 data or 4.87% if considered Atalić et al., 2021 data). The larger percentage of affected buildings in Zagreb, in mostly due to the fact that Zagreb building portfolio contains larger amount of masonry and historical buildings, especially from the group of unreinforced masonry (ESRM20). It must be mentioned that the last damaging earthquake in Skopje in 1963 has "cleared" considerable amount of masonry building stock in the city, and also afterwards with the city new urban reconstruction. Moreover, considerable amount of pre 1964 masonry structures in Skopje that exists today were strengthened to comply with the strength characteristics of the that time new 1964 code.

The similarities, impacts and lessons learned from those two earthquakes opens a wide space for further research with aim to build more effective system for response, creation of adequate preparedness measures and increase the resilience of urban systems.

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