Potres u Zagrebu od 22. ožujka 2020. - preliminarni izvještaj o seizmološkim istraživanjima i oštećenjima zgrada

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Zagreb earthquake of 22 March 2020 – preliminary report on seismologic aspects and damage to buildings

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Research Paper

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Zagreb earthquake of 22 March 2020 – preliminary report on seismologic aspects and damage to buildings

Significant characteristics and main consequences of the 5.5 magnitude earthquake that struck Zagreb and its surroundings in the midst of the COVID-19 pandemic are presented in the paper. Although, from the seismologic aspect, the earthquake was of moderate magnitude, it caused the loss of one life and considerable material damage. An overview of the situation before the quake is given, and information about the location, seismic activity, and organisation of building inspection activity, is presented. The data on damage are roughly classified, with the focus on historic core of the city and districts situated close to the epicentre. A strong emphasis is placed on indispensable activities that should have been carried out a long time ago, in the hope that they will be prompted by this earthquake.

Key words:
Zagreb earthquake, post-earthquake building inspections, masonry buildings, damage, historic core, cultural heritage

Prethodno priopćenje

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Potres u Zagrebu od 22. ožujka 2020. - preliminarni izvještaj o seizmološkim istraživanjima i oštećenjima zgrada

U radu su opisane bitne značajke i glavne posljedice potresa magnitude 5,5 koji je u jeku pandemije virusa COVID-19 zadesio Zagreb i okolicu. Premda je potres, seizmološki gledano, bio umjerene magnitude, prouzročio je gubitak jednoga života i veliku materijalnu štetu. Napravljen je pregled stanja prije trešnje te prikaz lokacije, seizmičke aktivnosti i organizacije pregleda zgrada. Grubo su razvrstani podaci o oštećenjima, s težištem na povijesnoj jezgri i četvrtima blizu epicentra. Na kraju su istaknute nužne aktivnosti koje je odavno trebalo provesti, s nadom da će ih ovaj potres potaknuti.

Ključne riječi:
potres u Zagrebu, pregledi zgrada nakon potresa, zidane zgrade, oštećenja, povijesna jezgra, kulturna baština

Vorherige Mitteilung

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Erdbeben in Zagreb am 22. März 2020 - vorläufiger Bericht über seismologische Phänomene und Gebäudeschäden

Die Arbeit beschreibt die wichtigen Merkmale und wichtigsten Folgen des Erdbebens der Stärke 5,5, das Zagreb und seine Umgebung inmitten der COVID-19-Virus-Pandemie getroffen hat. Obwohl das Erdbeben aus seismischer Perspektive eine mäßige Stärke hatte, verursachte es den Tod eines Menschen und großen materiellen Schaden. Es wurden eine Übersicht über den Zustand vor dem Beben sowie eine Darstellung des Standorts, der seismischen Aktivität und der Organisation der Gebäudeinspektion erstellt. Die Schadensdaten wurden grob klassifiziert, wobei der Schwerpunkt auf dem historischen Kern und den Stadtteilen in der Nähe des Epizentrums liegt. Schließlich wurden die notwendigen Aktivitäten hervorgehoben, die vor langer Zeit hätten durchgeführt werden sollen, in der Hoffnung, dass dieses Erdbeben sie anregen wird.

Schlüsselwörter:
Erdbeben in Zagreb, Gebäudeinspektionen nach dem Erdbeben, Mauerwerksgebäude, Schäden, historischer Stadtkern und Kulturerbe

1. Introduction

On Sunday, 22nd March 2020, a magnitude 5.5 earthquake hit the metropolitan area of Croatia's capital, Zagreb at 06:24 am local time. The earthquake originated in the Medvednica fault zone located just north of the city with the epicentre in Markusevac. The intensity at the epicentre is estimated at VII-VIII degrees on the Mercalli-Cancani-Sieberg (MCS) scale. The main shock was followed by a magnitude 4.9 aftershock at 07:01 am [1].

Despite having seismologically moderate magnitudes, these earthquakes caused a tragic loss of one human life and tremendous material damage currently estimated in excess of € 10 billion. It is estimated that approximately one fifth of the building stock, or up to 25.000 buildings, was affected by the earthquake and that around fifteen to twenty thousand residents were displaced from the central part of the city as a result. Material damage was particulary severe in the epicentral region as well as in the protected historic centre of the city which abounds with culturally important unreinforced masonry buildings. Specifically, many elements of critical infrastructure, such as schools and hospitals, as well as crucial administrative buildings were severely damaged and rendered unusable following the earthquake. In addition, many protected cultural monuments, museums and sacral buildings such as the Zagreb Cathedral, were also damaged (Figure 1). The low number of human casualties is primarily attributed to predominantly minor to moderate damage to structural systems of residential buildings, where only about five hundred residents required temporary shelter which was provided in student housing of University of Zagreb. A further mitigating factor was a reduced activity of residents due to the imposed restrictions related to the COVID-19 pandemic. Gatherings were banned, which was especially important for centuries-old churches that suffered heavy damage and where mass services would have been held under normal circumstances. Furthermore, there were only few people in the streets as otherwise many lives might have been lost due to collapses of numerous chimneys, parapets, gable walls, and other unsupported parts of buildings. Since many people left Zagreb just a couple days before the earthquake when the anticipated pandemic-related travel ban was enforced, the effects of seismic action on local population cannot be fully separated from the effects of the current pandemic.

The following sections present basic seismological data on the main shock and subsequent aftershocks. Furthermore, an overview of the earthquake preparedness and risk awareness before the event is presented along with information on establishment and implementation of post-earthquake building evaluation and extensive data collection efforts. An overview and classification of the observed structural and non-structural damage is provided along with description of numerous challenges stemming from subpar pre-earthquake preparation as well as due to COVID-19 considerations. The paper mainly presents the data from the City of Zagreb, as the damage in the neighbouring Zagreb County and Krapina-Zagorje County, was far less extensive.

Finally, a key part of this paper are recommendations aimed at ensuring future seismic resilience of Zagreb as well as resilience of Croatia to natural hazards. The authors were the lead organizers and participants in the post-earthquake building evaluations and have been advocating for seismic safety and risk mitigation for years leading up to the earthquake. This includes, for instance, development of national risk assessment documents [2, 3] which specifically identified Zagreb as a risk hotspot with many deficiencies related to earthquake preparedness. Unfortunately, thus far the seismic safety and risk mitigation advocacy has not been met with systematic support and commitment from pertinent stakeholders and policy makers and as such the authors feel the consequences of this devastating event resting heavily and bindingly on their shoulders. With the prospect of an expected magnitude 6.5 event on the Medvednica fault zone still looming large, it is imperative that we collectively take this seismologically moderate yet extremely disruptive event as a stern warning to stop ignoring this burning issue. This is our opportunity for encompassing collaborations between researchers, practicing engineers, seismologists, architects, and government officials on projects, strategies and initiatives that will have impactful and long-lasting effects as we forge our path towards a resilient future.

2. City of Zagreb: basic data about the location

The City of Zagreb, as the national capital, is not only the administrative centre of the Republic of Croatia, but also the regional and cultural centre of notable significance. The city is home to important educational, cultural, arts and healthcare institutions, industrial plants, and cultural heritage assets of exceptional national and international significance. In fact, Zagreb can be regarded as the principal economic centre on the national level, considering the structure of economy, industrial capacities and percentage of city's budget as compared to other

Figure 1. Earthquake effects in historic centre of the city (photos courtesy of: AIR-RMLD d.o.o. www.air-rmld.com, Filip Foretić, Karlo Jandrić)

cities in Croatia. For instance, according to the data published by the Croatian Bureau of Statistics regarding the gross domestic product, as much as one third of the total Croatian economy is concentrated in this city. On the other hand, a large number of national administrative bodies with their seats in the city points to the significance of Zagreb for the administrative and political stability of the country. Furthermore, Zagreb is the national centre of road, rail and air transport, and the actual crossroads of European east-west and north-south transport routes.

According to the 2011 population census, this city spreads over an area of 641.37 km^2 and has 790,017 inhabitants (approximately 20 % of the Croatia's population) or, on the average 1,213 persons per km^2. The city is administratively divided into seventeen city districts (CD) and 218 local board districts (LB). The most populated CDs are CD Donji grad with 12,274 inhabitants per km^2 and CD Trešnjevka – north with 9,542 inhabitants per km^2. The least populated CDs are CD Podsljeme with 928 inhabitants per km^2, and CD Brezovica with only 85 inhabitants per km^2. The historic centre of the city, with most individual stationary cultural assets (about 400 in total) and most of protected urban entities (Figure 2.b), lies immediately below Medvednica in CD Donji grad (marked in Figure 2.a) and in some parts of neighbouring CDs.

It is known that the city of Zagreb is situated in a seismically active region, as dramatically proven by the historic 6.2 magnitude earthquake that struck the city in 1880 and caused enormous damage and emigration of local population [4, 5]. The Zagreb Cathedral also suffered extensive damage during that earthquake (Figure 3) and gained its present day appearance, more precisely appearance until recently, after thorough reconstruction which lasted until the early twentieth century. It can generally be concluded, that it is precisely because of the comprehensive general reconstruction conducted after the 1880 earthquake, that Zagreb evolved from a small provincial town to a modern urban centre. We sincerely hope that also after this earthquake, almost a century and a half after the previous one, not only that seismic damage will be thoroughly and professionally remedied, but that comprehensive urban renewal of the city shall be accomplished.

As the earthquake risk has not been in the focus of experts in Croatia, herewith we aim to explain the relevant factors influencing the earthquake risk in Zagreb, including the basic definitions. The earthquake risk is normally defined as a combination of the probability that consequences (damage) will occur and the corresponding probability of occurrence of a seismic event [5]. It is expressed as a convolution of individual factors: seismic hazard, exposure and vulnerability, which will be briefly described below, while interested readers are referred to [5] where a more detailed description is given. Seismic hazard comprises potentially destructive effects of an earthquake (such as ground motions, liquefaction, landslides, etc.) at a given location. It is expressed through a statistical probability of exceedance of a selected parameter over a given period, such as the peak ground acceleration or spectral acceleration. Exposure can be defined as the extent of human activity (e.g. presence of buildings) in areas exposed to seismic hazard. The most significant part of the data on exposure is related to the inventory of existing buildings (building stock) that significantly contributes to the societal and economic risk. Physical vulnerability can be defined as susceptibility of exposed buildings to earthquake effects (damage), and the objective of its estimation is to define the probability of occurrence of a certain level of damage to a particular type of building due to seismic action. In the territory of the Republic of Croatia, seismic hazard is defined by the currently valid Croatian seismic hazard map [6], according to which Zagreb and its surroundings are

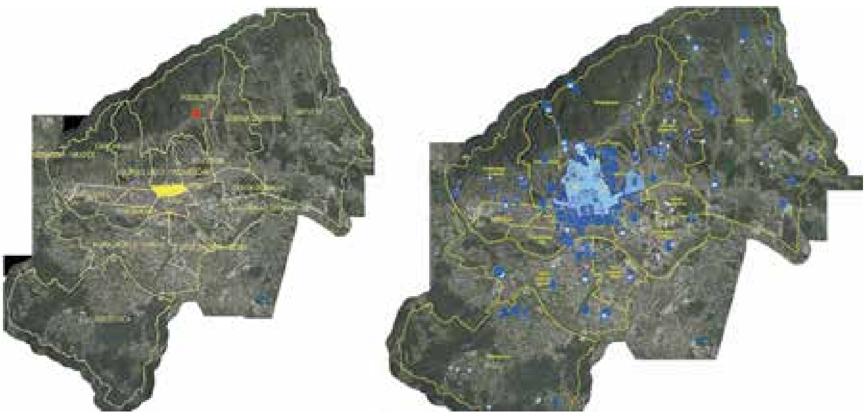


Figure 2. Map of Zagreb: a) Distribution of city districts (CD) with an emphasis on CD Donji grad (marked in yellow) and epicentre of the mainshock (marked with red circle) and b) position of historic urban entities (source: https://geoportal.zagreb.hr/karta)

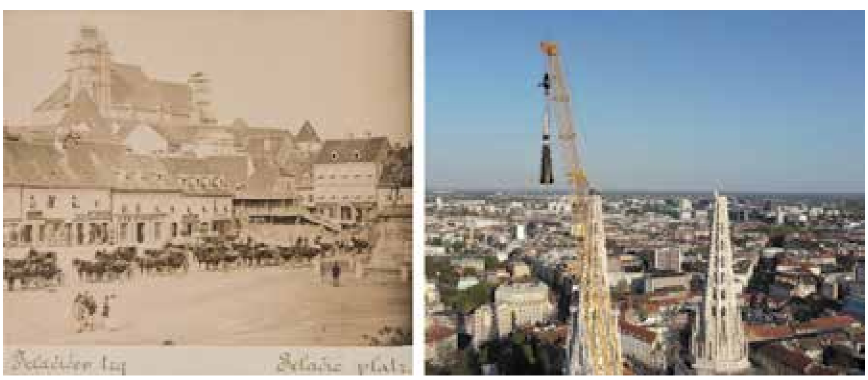
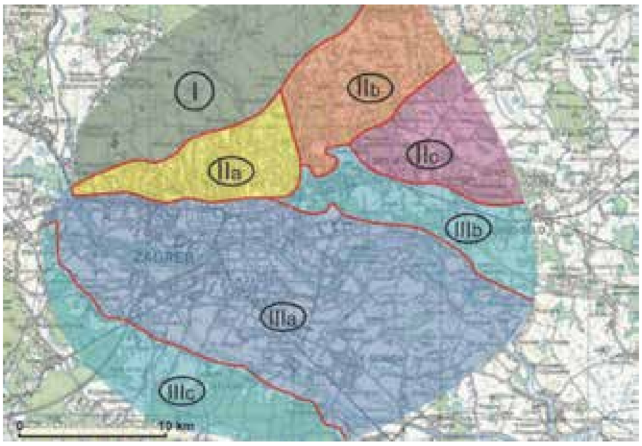


Figure 3. Zagreb Cathedral – tower removal: a) after the 1880 earthquake (source: Museum of the City of Zagreb), **b) after the 2020 earthquake** (source: Ministry of Defence of the Republic of Croatia)



Mark	Description
I	Mountainous core of Medvednica
II	Medvednica foothills – Urbanised zone below Sljeme
IIa	Periclinally positioned younger formations (Neogene and older Quaternary formations)
IIb	Folding structure in younger formations (Neogene formations)
IIc	Older Quaternary elevated zone and mountain creek sediments
III	Sava River boundary flood plain
IIIa	Sava River flood plain
IIIb	Terrace elevations (terraces)
IIIc	Terrace elevations (terraces)

Figure 4. Macro-zoning of wider area of Zagreb according to geologic-topographic-hydromorphologic criteria [7]

likely to experience peak ground accelerations at the bedrock level of 0.20-0.28g for the return period of 475 years. Most ground types (Figure 4) correspond to types B and C according to classification in concordance with the standard for the design of structures for earthquake resistance HRN EN 199 [7-10].

Theoretical studies on linear amplification of earthquake motion in Zagreb, as based on a hybrid procedure for generation of synthetic accelerograms (modal summation, and modelling by finite differences), were published by Lokmer et al. in 2002 [11] and Herak et al. in 2004 [12].

Seismic hazard in Zagreb area mainly originates from the Medvednica epicentral zone, although the influence of earthquakes in the vicinity of Ivančica, Brežice, Krško, and even more distant areas such as Pokuplje or Žumberak, should not be neglected. Many papers, such as [13–20], have been published about the tectonics of the wider Medvednica area. Herak et al. reported in 2009 [21], on the seismicity of the north-western parts of Croatia, including the Zagreb area. In that paper, the authors briefly presented the seismic history, and described faulting mechanisms available at the time, while also providing an analysis of locations of hypocentres and their relationships with assumed active seismogenic faults. Seismotectonic features of the Medvednica area were presented by Herak et al. in 2019 [22]. Reverse Northern Medvednica boundary fault (SRMR), striking along the north-west boundary of Medvednica (with the fault inclining downwards toward the south-east), and the Kašina strike-slip fault (KR), approximately perpendicular to the Medvednica fault, have been identified as seismic sources that are of the highest significance for the city of Zagreb. Some other reverse faults (such as the Sljeme fault), of yet unproven seismogenic activity, have also been identified below Medvednic [16] Figure 5 shows the main faults in the vicinity of Medvednica (simplified according to [22]), as well as the epicentres of earthquakes with the local magnitude of $M_L > 0.5$ accurately located in the period from 1975 to 2018 (blue), and a series of earthquakes that occurred from 22 March 2020 to 5 May 2020 (red).

Figure 5 shows earthquakes with magnitudes $M_L > 0.5$, and with the epicentre within the seismograph network (maximum continuous station azimuthal gap of $\gamma < 180°$). Red lines show surface traces of fault systems in the Zagreb area (simplified according to [22]): SRMR – Northern Medvednica boundary fault, KR – Kašina fault). Triangular marks denote hanging walls of reverse faults, while arrows indicate direction of relative displacement along the strike-slip faults.

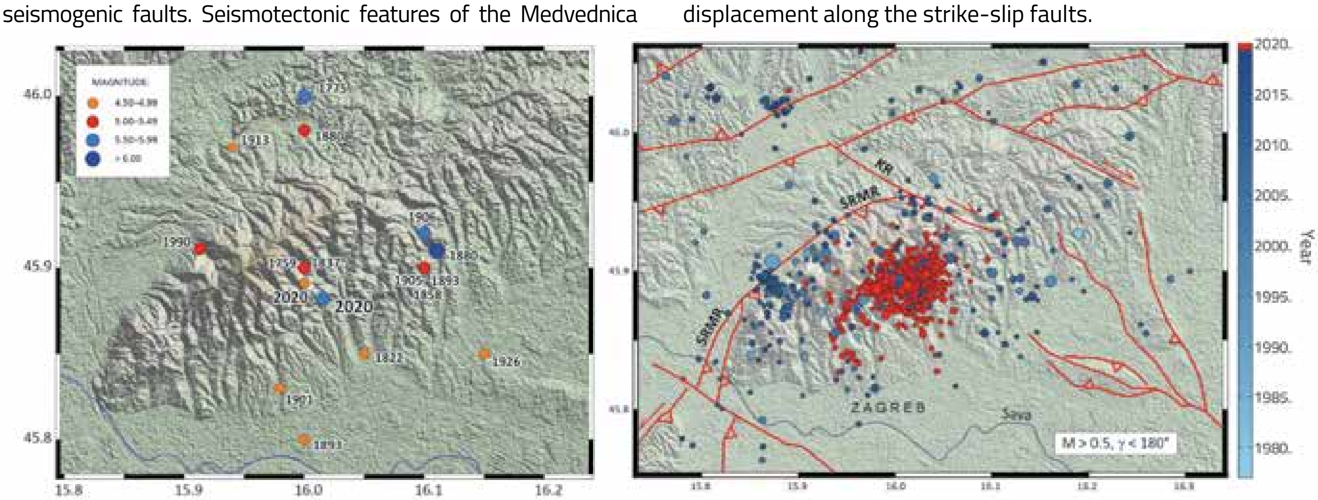


Figure 5. a) Epicentres of earthquakes with the magnitude 4.5 or larger in the wider area of Zagreb, with the year of each event; b) Epicentres of earthquakes accurately located in the period from 1975 to 2018 (blue) and a series of earthquakes in 2020 (red)

Although the big earthquake of 1880 is usually the one mentioned when historical earthquakes in Zagreb are discussed, it is also interesting to consider the overview of seismic history of the city of Zagreb. Figure 6 shows earthquake intensities in the centre of Zagreb (according to Mercalli-Cancani-Sieberg scale, MCS) for all earthquakes contained in Croatian catalogue of earthquakes, as described by Herak et al. [23]. Physics. The intensities presented in this Figure were calculated using empirical relations that link seismic intensity in the epicentre (I_0), earthquake magnitude (M_L), hypocentral depth (h), distance from the epicentre (D), and seismic intensity at the studied location (I_L), Eq. (1) [24] and Eq. (2), according [25]:

$$M_L = 0{,}721\, I_0 + 1{,}283 \log h - 1{,}130 \tag{1}$$

$$I_L = I_0 - 3\log(R/h) - 3\,\mu\alpha(R - h),\ R = (D^2 + h^2)^{1/2}$$
$$\mu = \log(e) = 0{,}43429,\ \alpha = 0{,}005\ \text{km}^{-1} \tag{2}$$

As is the usual practice for earthquake intensities, these relations assume the so called "average soil" for which no formal definition exists, and which describes the soil of average amplification properties in a large area. For soils of lesser quality (such as soft clay) or for better-than-average soils (such as solid rock), it is normal practice to add to (or deduct from) the calculated intensity an intensity increment to take into account the expected (de) amplification in wave motion within surface layers of soil.

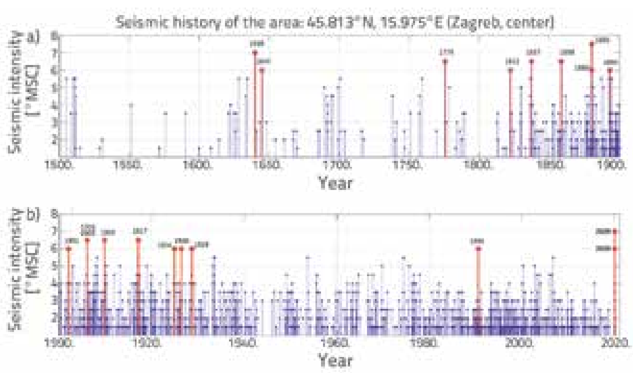


Figure 6. History of earthquakes in Zagreb (city centre). a) from 1500 to 1899; b) from 1900 to 2020

Each bar in Figure 6 corresponds to one earthquake from the Croatian Earthquake Catalogue ([26], updated in 2019), with the calculated intensity in the Zagreb city centre of more than 1.0° MCS. Earthquakes with the intensity of 6.0° or more MCS (on average soil) are marked in red. The intensities are rounded to a half degree. The isotropic macroseismic field and the so called average soil (no intensity increment) is assumed.

Figure 6 is related to the Zagreb centre (central part of Zagreb) and it would be noticeably different if the calculations were made for instance for Markuševec, Novi Zagreb, or Podsused. The figure provides only an approximate estimates of intensity, as it does not take into account amplification in the topmost soil layers, anisotropy of macroseismic field, earthquake mechanism, topography, etc.; the real intensity can be obtained only after the conducted macroseismic investigations. It can however be noticed that in the past period of only two hundred years there were as many as 16 earthquakes in Zagreb, with the estimated intensity of VI° MCS or more, that were thus capable of causing damage. The most significant among them were the earthquakes in: 1837 (Medvednica), 1858 and 1905 (Prekvršje), 1880 (Planina), 1906 (Planina – Kašina), 1909 (Pokuplje – Vukomeričke gorice), 1917 (Brežice) and 2020 (Markuševec) (cf. Figure 5). Unfortunately, only the big Zagreb earthquake of 9 November 1880, and the famous 1909 Pokuplje earthquake, were adequately macro-seismically analysed. It would therefore be worthwhile to re-examine available historical data, to collect new data if possible, and to re-check and, if necessary, correct the hypocentres, intensities, and magnitudes estimated for these earthquakes. For instance, preliminary investigations have revealed that the intensity of the earthquake of 17 December 1905, as marked in the catalogues, is overestimated. The analysis of macroseismic data for the Markuševec earthquake of 22 March 2020 is in progress. Such analyses will be very valuable during preparation of a new seismic hazard map.

In addition to seismic hazard, properties of buildings and other infrastructure in a given area also form a significant component of risk assessment. Almost one third of all housing units currently existing in Zagreb were built before 1964, i.e. before the first seismic regulations were introduced in the former state (after the 1963 Skopje earthquake). In other words, these buildings were not even designed to withstand seismic load. Additionally, more than one half of housing units are situated in buildings built after 1964 and until the application of modern standards, i.e. during the time period when the prescribed level of seismic action was several times lower than today [2, 27–29]. The European standards for the design of structures for earthquake resistance (Eurocodes) have been officially in force since 2005 for concrete buildings and since 2007 for masonry buildings (ENV pre-standards), with the use of the seismological map from 1987. The new seismological map from 2012 became officially valid together with the EN standard series, although the use of Eurocode 8 was not mandatory for all buildings before the year of 2017.

It should be noted that buildings have over the years often been renovated, not always in compliance with rules of professional practice, and were thus additionally weakened. In addition, materials of load bearing elements, such as mortar and brick, deteriorate over time and lose their mechanical properties. Thus, it is intuitively clear that a considerable number of Zagreb buildings is highly vulnerable to earthquakes. In conclusion, Zagreb area is characterized by moderate to high seismic hazard, high exposure (due to great population density, cultural heritage, significance of the city) and high level of vulnerability of buildings (due to unfavourable design of load bearing structures, age, poor maintenance, illegal construction and renovations). That is why the earthquake risk of the city is very high. According to the last official national seismic risk assessment, the worst-case scenario for this city would result in a direct monetary loss of € 16 billion for housing stock, with great damage and collapse of buildings, and in the loss of almost 3,000 human lives [2, 3, 5]. Unfortunately, although warnings about high seismic risk have been repeatedly issued over many years by scientific community - some of the earlier ones dating back to Mohorovičić lectures given to civil engineers and architects in 1909 [30, 31],this problem, crucial for the safety of citizens, stable development, and preservation of cultural heritage of the Republic of Croatia, has not been adequately recognised by relevant persons and institutions, nor has its resolution been appropriately backed by professional and research activities.

3. Mainshock and subsequent seismic activity

The mainshock of the earthquake series hit the area on 22 March 2020 at 05:25 UTC, and its local magnitude was M_L = 5.5 on the Richter scale (moment magnitude M_w = 5.3). The epicentre was in Markuševec, and the hypocentre was at the depth of approximately 8 km. According to preliminary intensity data, the epicentral intensity is estimated at VII-VIII degrees on the MCS scale. The strongest aftershock occurred on the same day at 06:01 UTC (M_L = 4.9, M_w = 4.7). A total of ten more earthquakes with the magnitude of M_L ≥ 3.0 was recorded during the series (i.e. until the time this part of the paper was written – May 2020). In total, more than 1,400 earthquakes were recorded during the first forty-five days of this earthquake sequence.

The Gutenberg-Richter relation describing the distribution of magnitudes of aftershocks indicates that the earthquake catalogue is complete for the magnitudes of M_L > 1.0 (there were 724 of such earthquakes in total), which is an excellent result considering the density of seismic stations in the Zagreb area. In fact, only two seismic stations (Zagreb and Puntijarka, and four additional strong-motion stations) operated prior to this earthquake in the 20 km circle around the epicentre. There are two additional Croatian stations (Lobor and Kalnik), and three Slovenian stations, in the 50 km circle around the epicentre. Two days after the mainshock, three temporary stations were installed in Kašinska Sopnica, Rugvica and Čret.

Earthquake hypocentres were located using the Hyposearch program [23] which was adapted to use the source-specific station corrections. In the iteration process, the program adjusts optimum locations and makes necessary systematic corrections of observed onset times of seismic phases at individual seismic stations, so as to minimise the influence of the selected Earth interior model on the final result. Figure 7 shows epicentres of the earthquakes accurately located during the first 45 days after the mainshock of 22 March 2020. Focal depth is colour-coded, and most of the values range between 3 and 10 km in depth. Most epicentres are situated to the east of the Bliznec Creek, within the area measuring approximately 6.5 km x 4.0 km, which excellently coincides with the spatial distribution of maximum ground displacements defined by preliminary analysis of the DInSAR satellite data (M. Govorčin, 2020, personal communication). However, smaller concentrations of epicentres are also visible outside of this area (such as the one at the south-western end of the epicentre cloud in the Pantovčak area), which shows that perhaps some smaller surrounding faults were also activated. Hypocentral depths generally increase in the NW-SE direction, which is in accordance with the assumed geometry of the Northern boundary Medvednica fault. All earthquakes with the magnitude of M_L ≥ 3.0 occurred at the depths ranging from 6 to 9 km. The fault mechanism solutions for the mainshock and for two aftershocks (at 06:02, M_w = 4.7 and at 06:41, M_w = 3.3) were computed using the data on polarity of the first motion of the P-wave (Figure 7). Solutions for the mainshock and the largest aftershock are very similar and point to conclusion that earthquakes occurred on a purely reverse fault inclined either toward NNW or toward SSE. Hypocentre positions give clear preference to the second possibility. The solution for the weaker aftershock is less reliable and also points to prevalently reverse fault, but with a small strike-slip component. Considering the different strikes od possible fault planes, we might have here an activation of a smaller fault. International agencies and organisations (such as NEIC, GFZ, SLU, OCA, INGV) have published their moment tensor solutions for these events, which agree with those presented in Figure 7. The inferred axis of the maximum tectonic pressure strikes SSE-NNW, which is in accordance with the current state of knowledge for the north-west of Croatia (cf. for instance in [21]).

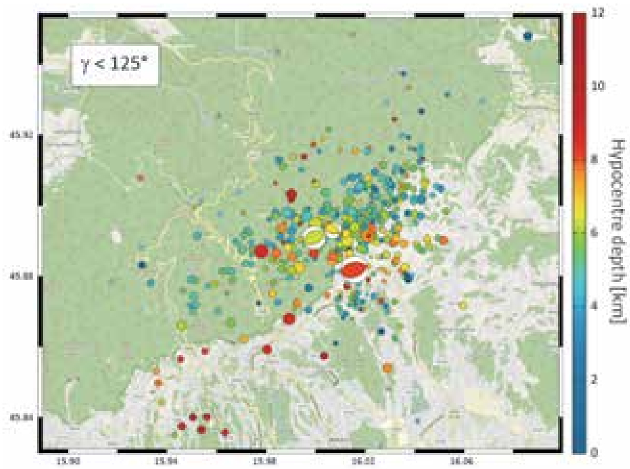


Figure 7. Preliminary locations of seismic epicentres, 22 March 2020 to 5 May 2020

Figure 7 shows only the earthquakes recorded by seismic stations uniformly distributed in space (with the maximum continuous azimuthal gap of γ < 125° with regard to the epicentre). The focal depth is colour-coded according to the colour scale given on the right-hand side of the Figure. Three fault mechanism solutions are also presented (lower focal hemisphere in stereographic projection) for the mainshock and two aftershocks; the compressional quadrants are marked with the colour corresponding to the hypocentral depth.

At the moment this section was being prepared (May, 2020) aftershocks had not as yet ceased to occur, and so all the information presented in the paper is of preliminary nature only. The final locations of all earthquakes, description of the macroseismic field, conclusive statistical, geologic, geodetic and seismotectonic analyses (e.g. the identification of the seismogenic fault and faulting details), and analyses of the engineering-seismological features of this earthquake series, will be possible only after the seismic activity ceases, and after all available data are collected and carefully analysed.

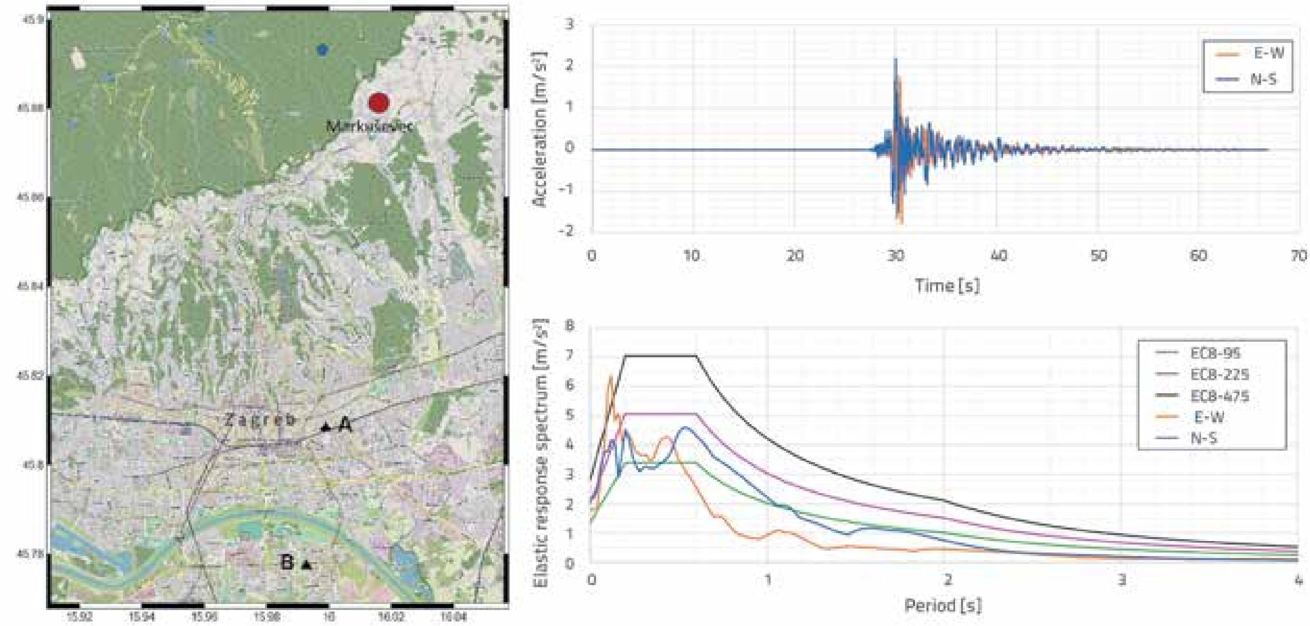


Figure 8. a) Location of strong-motion stations A and B (black triangles) where the mainshock (M_L = 5.5, red circle) and the strongest aftershock (M_L = 4.9, blue circle) were recorded; b) ground accelerations in horizontal directions (north-south N-S and east-west E-W) recorded during the mainshock at the location A [32]; c) elastic response spectra of recorded motions and elastic response spectra for the location A and assumed ground type C according to valid standard HRN EN 1998-1

The earthquake occurred in the midst of the Covid-19 virus pandemic. This fact greatly affected the response of seismologists, as all procedures usually undertaken immediately after the earthquake (and later on as well) were either made more difficult or prevented. However, small seismological community in Croatia has made the best of the situation, so that the public could not even notice that colleagues from the Croatian Seismological Survey and the Geophysical Institute operating within the Department of Geophysics of the Faculty of Science mostly worked from home, that the communication was mostly done online, and that field work was complicated by the situation. In addition to their day to day activities, these experts regularly submitted reports to relevant authorities, organised installation of additional instruments, performed macroseismic reconnaissance, promptly analysed numerous aftershocks, and communicated with general public either *via* statements and interviews for media, or *via* the internet pages and through social networks moderated by our colleagues-seismologists.

According to the data provided by the Seismological Survey [32], both the mainshock (M_L = 5.5) and the strongest aftershock (M_L = 4.9) were recorded by accelerographs installed at locations A and B (Figure 8), situated 8.2 and 11.7 km, respectively, from the epicentre of the mainshock. During the mainshock, the peak acceleration on foundation soil recorded at locations A and B amounted to a_{maxA} = 0.22 g and a_{maxB} = 0.20 g, respectively. Recorded ground motions in horizontal directions north-south (N-S) and east-west (E-W) at location A during the main shock are presented in Figure 8.b [32]. The peak ground acceleration of the strongest aftershock (M_L = 4.9) amounted to a_{maxA} = 0.07 g and a_{maxB} = 0.04 g. As none of the accelerographic stations is located on the bedrock, these accelerations should be corrected so as to estimate the reference peak acceleration for the type A (a_g) foundation soil. As seismic microzoning has not as yet been conducted for this part of Zagreb, the type of soil cannot accurately be determined at this time. However, location A is situated very close to the southern periphery of the area for which the microzoning was performed (Podsljemenska zona, [10]), and, as type C soil is dominant throughout its southern part (with smaller patches of type B soil), it can reasonably be assumed that type C or B-C soil would prevail at location A as well. The soil type C is even more probable for the location B situated south of the Sava River, within the Sava flood plain, where bedrock is expected to be rather deep. According to regulations in force, the amplification of peak acceleration for this type of soil amounts to S = 1.15 (soil factor for type C soil and type 1 spectrum which is in official use in our country). Before a more detailed analysis, which is currently being prepared [32] it can only be stated that the expected amplification of peak acceleration probably does not exceed 20 % at both locations. According to the seismic hazard maps [6] used for design purposes, for location A we have a_g = 0.12 g for the return period of 95 years, and a_g = 0.25 g for the return period of 475 years. For the location B, these figures are quite similar: a_g = 0.12 g (95 years) and a_g = 0.24 g (475 years). Figure 8.c shows the elastic response spectra of the recorded motions in the directions north-south (N-S) and east-west (E-W) at the location A during the main shock and elastic response spectra according to valid standard HRN EN 1998-1 for the location A and assumed ground type C, for different return periods (95, 225 and 475 years).

4. Organisation of the disaster response system

4.1. Situation prior to the earthquake

To enable better understanding of the general effects of the Zagreb earthquake, it is indispensable to present to readers the system organised in response to the COVID-19 crisis, and the general situation as related to the pandemic. Only three days before the earthquake, Civil Protection Headquarters of the Republic of Croatia issued a decree on ban of public and religious gatherings and sporting events, and on suspension of operation of food establishments, stores (except for grocery shops and pharmacies), and sports and recreation centres. A day before the earthquake, strict limitations were issued with regard to any group gatherings on streets and in other public places where a greater number of persons can simultaneously walk or be present at (such as squares, seafront promenades, parks and other public spaces). In addition, a temporary ban was introduced on the movement of persons across national borders, and the decision banning any departure from the place of residence in the Republic of Croatia was announced (the actual ban was issued on 23 March 2020). Because of that announcement, some Zagreb residents may have decided to temporarily leave the city (by moving for instance to their holiday homes), which could have influenced the number of victims, but which also complicated provisions of assistance and supplies from other parts of Croatia or from neighbouring countries.

The framework of the disaster response system has been set up relatively well, where organisation and education of intervention units, formation of MUSAR (medium urban search and rescue) teams, participation in numerous exercises, etc should be pointed out. The Croatian Platform for Disaster Risk Reduction, set up within the National Protection and Rescue Directorate (NPRD), which has been operating since the start of 2019 within the Civil Protection Directorate of the Ministry of the Interior (MUP) should be especially mentioned. The Emergency Management Office (UHS) operates at the local level of the City of Zagreb. This office organized various activities related to post-earthquake situations (exercises, acquiring equipment, etc.) and financed studies/projects in which various issues aimed at reducing consequences of earthquakes are considered. It should be pointed out, that the office of such capacities is a unique example in Croatia and that, in general, the frameworks of the national system and municipal system for the Zagreb area appear to be quite encouraging.

Unfortunately, this has proven to be insufficient considering the level of seismic risk, i.e. proportions of disaster events that can be expected in Croatia and Zagreb. For instance, a number of risk assessments have been made for the city of Zagreb [5], which includes two national-level assessments (officially issued in 2015 and 2019) in which the city of Zagreb was identified as the worst possible scenario for the Republic of Croatia. Despite numerous deficiencies and differences in results, it is clearly stated in all existing risk assessments that the earthquake presents one of the highest risks for the Republic of Croatia, with possible catastrophic consequences that might undermine stability of the country. In addition, in the scope of national–level assessments, earthquakes are defined as a risk that is unacceptable for the Republic of Croatia, but the activities of the relevant institutions do not conform to these conclusions. On top of that, even in the national development strategy (currently in preparation) seismic risk in not considered as an important element (it is mentioned only marginally), and so it seems that estimates are made only formally, ex officio (to fulfil obligations toward European Commission or to comply with our byelaws), i.e. they do not serve as a basis for systematic implementation of risk mitigation activities.

A question has often been asked (and it is still asked) about readiness, capability and capacities of the system in the case of an earthquake striking one of our larger cities. It is precisely the earthquake in Zagreb that has pointed out many of our weaknesses. At that, it should be noted that intervention teams in charge of search and rescue from debris remained practically inactive (as no building actually collapsed), and these teams were at the focus of preliminary activities (and investments) at the national and municipal level. It seems that the system has been devised for a much larger seismic event and, at that, the part related to assessment of building damage has been neglected. On top of that, no official forms for post-earthquake inspection of buildings actually existed, and no systematic training of experts that could take part in post-earthquake inspection of buildings has been organised. However, one should not forget individual initiatives that proved crucial for establishment of the system after the Zagreb earthquake, in the scope of which experts participated in education programs within various European projects, in numerous civil protection exercises and, finally, in the inspection of buildings following the recent earthquake in Albania, as a part of Croatian team for technical-tactical support [33]. Approximately twenty persons were educated in these activities, and they formed the core of the system for the inspection of damage to buildings after the Zagreb earthquake.

When discussing preliminary phases, a great problem in the assessment of damage and in considering the effects of the earthquake on the community was the non-existence of the database of buildings. Generally speaking, databases are a burning problem in Croatia, further complicated by the fact that potential official sources are also not systematized and connected and, in most cases, they are poorly maintained, inadequately updated and insufficiently modernised. Currently, there are no data about the number of buildings, let alone the data about plan view dimensions, cross sections, construction material used, occupancy, etc. Some limited data about housing units have been obtained through population census and, despite numerous efforts, the data about buildings have not been included in the new population census to be conducted in 2021. Such data are crucial for creation of a good quality database, which is highly necessary for risk assessments and strategic planning.

It can generally be concluded that community awareness about the earthquake risk has been minimal although the Republic of Croatia and neighbouring countries have been hit by earthquakes of the intensity that exceeds the one observed in Zagreb (for instance Dubrovnik $M_L = 7.1^*$ (1667), Zagreb $M_L = 6.2^*$ (1880), Pokuplje $M_S = 5.8$ (1909), Imotski $M_L = 6.2$ (1942), Makarska $M_L = 6.1$ (1962), Banja Luka $M_L = 6.4$ (1969), Skopje $M_L = 6.1$ (1963), Montenegrin littoral region $M_w = 7.0$ (1979), Ston $M_w = 6.0$ (1996), and Durres (Albania) $M_w = 6.4$ (2019); magnitudes marked with an asterisk are estimated based on the seismic intensity in the epicentre). We have been warned for years (almost on the monthly basis) by numerous smaller earthquakes, but public reaction or reaction of the society has in most cases been reduced to explanations, interpretations and opinions of various experts, and all has usually been rapidly silenced, without any follow up [5]. This is perhaps the basic problem during seismic risk mitigation activities, as relevant authorities and the community should work hand in hand, like for instance in Italy, where building owners are encouraged to strengthen their buildings through various programs, support schemes, tax deductions, and similar measures.

And finally, it must be admitted that the earthquake has struck the system that was not ready for it, and so the question arises about the future of earthquake risk mitigation activities considering the economic situation in our country and continuous lack of finances. But beware, as much stronger earthquakes have occurred in Zagreb and in Croatia before, they can be expected to strike again in the future!

Figure 9. Volunteers conducting on-site inspections

4.2. First hours after the earthquake

It has already been emphasized that on that early Sunday morning the city was deserted, which was a very lucky circumstance in the light of possible earthquake consequences. Civil protection services were immediately activated, and experts from the Faculty of Civil Engineering and the authors of this paper were urgently summoned based on many years of cooperation with these institutions, to provide assistance in organisation of the system and in establishment of the crisis management unit for operative on-site management of building damage assessment activities. At that time, proportions of the disaster were not known, and the decision was made that the office of this crisis management unit be organised at the premises of the Emergency Management Office.

In the first hours after the earthquake, the experts already trained for inspections at first inspected hospitals in the old part of the town, which suffered moderate to considerable damage. At the same time, inspections were independently organised to check condition of the Sava bridges – most of them built over fifty years ago – as they are of crucial significance for proper functioning of the city. As the number of calls by citizens reporting damage increased with every passing hour, and as most engineers did not undergo necessary training, additional professionals with experience in the post-earthquake inspection of buildings and in post-war reconstruction activities, as well as experts having necessary expertise of traditional masonry structures were invited first. Shortly afterwards, in cooperation with the Civil Protection Directorate of the Ministry of the Interior, a proposal was made to mobilise civil engineers (structural engineers in particular) via the Croatian Chamber of Civil Engineers, which generally provided great assistance in these efforts. Within the first day after the quake, more than 150 engineers responded to volunteer in the rapid assessment of building damage, and all of them were provided with necessary protective equipment (hardhats, vests, etc.) in the UHS office, so that they could safely enter the damaged buildings, and also with masks, gloves and disinfectants (hand sanitizers) because of the pandemic. Numerous benefactors and donors continuously provided assistance to counter the shortage of protective masks and additional equipment. Soon the unit was contacted by colleagues from other parts of Croatia and from neighbouring countries but, due to closed borders and ban to leave the place of residence, they were unable to come to Zagreb.

In the first week, the number of volunteers (Figure 9) rose to over 500 engineers, but the work of individual teams greatly depended on regular work duties of participating experts.

Initially the inspections were made based on urgent calls but, later on, they were organised based on observations and damage reported by citizens. Affected residents were able to report damage via telephone calls, by email and soon afterwards via Internet once relevant pages were made available by the City. In addition to damage inspections, municipal and national civil protection departments organised debris clearing and removal of potentially dangerous parts of buildings. This task was conducted under guidance of the Public Fire Brigade of the City of Zagreb, which was also aided by alpinist volunteers, and climbers trained for work at large heights, and all of them used data from the on-site building inspections. The Croatian Red Cross provided lodgings, food and accommodation for persons who lost their homes, and a tent settlement was also erected. Numerous activities were conducted simultaneously, organized by municipal and national headquarters formed after the earthquake.

4.3. Preliminary on-site inspections of usability of buildings

As an official form for post-earthquake building inspections was not defined in advance, the template of this form developed in the scope of the *Study on Seismic Risk Mitigation* was used, which has been conducted for many years in cooperation between the Faculty of Civil Engineering and the Emergency Management Office [28]. The basic content of the form was defined based on experience from Italy [34], and then the form was gradually adjusted to conditions specific for Croatia. The printed form was used during the first two days (Figure 10), but the design of a digital form was initiated already on the first evening using an application based on the ArcGIS Online geo-information platform.

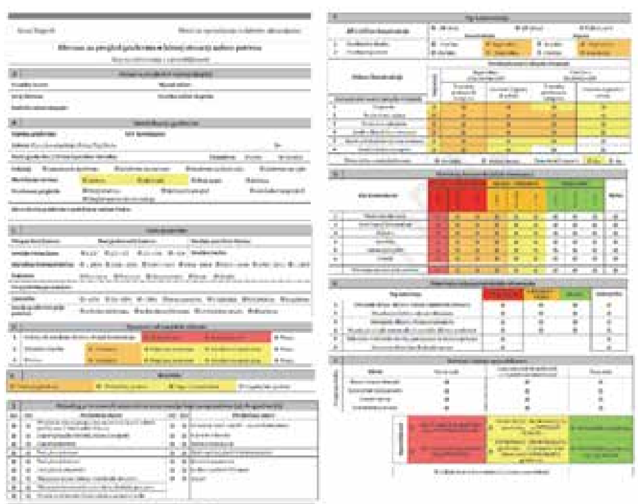


Figure 10. Form for post-earthquake inspection of buildings

In the application *Collector for ArcGIS*, which was adjusted for collecting on-site information (Figure 11) [35] the form was simplified, i.e. adjusted to the on-site situation (according to the feedback on typical observed damage received from inspection campaigns), and the application was in full use already of the third day after the earthquake. The *Collector for ArcGIs* can be installed on personal computers and mobile phones. It was proven to be quite adequate during rapid assessments conducted after the Zagreb earthquake. In fact, the experts that used this application in building inspections expressed satisfaction with the way it operated. Another application for on-line reporting of building damage, based on *ArcGIS Survey* poll, enabled map-based direct reporting of damage, which accelerated communication with experts performing the inspections.

The mobile application accelerated building inspections considerably as it enabled direct entry of required parameters, and it also greatly reduced the number of contacts (especially with the headquarters), which was highly appropriate because of the pandemic. In addition, the application enabled geo-spatial monitoring of teams in real time, which facilitated coordination i.e. sending the crews to critical areas. The data were stored in the *Esri Geospatial* cloud, and searches and analyses of data were conducted on a daily basis, with a particular importance given to on-site photographs that provided better insight into the condition of buildings.

This high practical usability of the application proved significant in the face of two simultaneous hazards – earthquake and pandemic. The data with addresses of people in home isolation were added in the scope of subsequent development of the application. In the first week, these data were gathered from people reporting the damage. However, it soon became clear that these data are not fully reliable, as some residents did not report home isolation status out of fear that their building would not be inspected. A five-day stop of inspection work was needed to protect the health of experts performing inspections, i.e. during this time appropriate harmonisations were made to enable direct connection with official data about addresses of people in home isolation. This period was also used to make additional adjustments in the light of problems observed during on-site inspections of buildings. After inspections resumed, the data about home isolation were received every day from the Croatian Institute of Public Health and, by strict application of epidemiological instructions, the risk of infection spreading among on-site experts was reduced considerably. About two hundred volunteers – mostly civil engineers and architects - were working on building inspection duty every day. Sometime later (two weeks after the earthquake) the City of Zagreb offered compensation for the inspection work, which was accepted by approximately one half of the experts, while the remaining experts continued to work on voluntary basis.

During the first days, the focus was on the assessment of buildings safety, because it was necessary to rapidly determine and apply measures to reduce the risk of collapse or fall of parts of buildings onto neighbouring buildings and/or onto approaches to buildings, to provide temporary accommodation for people, and to gain preliminary insight into the extent of damage inflicted by the earthquake. After the on-site assessment of damage, inspected buildings were marked as follows: green (can be used without limitations – U1, or can be used with recommendation for short-term countermeasure – U2), yellow (temporarily unusable, detailed inspection needed – PN1, or building can become usable after performing urgent interventions – PN2) and red (unusable due to external risks – N1, or unusable due to damage – N2). Fire brigades and municipal services had direct insight into building inspection data, which enabled them to take urgent actions such as: removal of debris, removal of damaged and collapsed chimneys, removal of hanging parts of facades, and elimination of other items if considered potentially hazardous to human life. In addition to fire brigades, the insight into the number of damage reports and usable buildings was also provided, depending on the level of authorisation, to various municipal services and ministries, which enabled transparency and proper exchange of data up to the required level. Special attention was paid to buildings belonging to critical infrastructure, and decisions on their usability were made in consultations with the headquarters and management of these buildings.

As many experts did not have any experience with usability assessment of buildings and with defining the level of damage, quality assurance and harmonisation of individual assessments, while inspections were in progress, proved to be a considerable challenge. In general, the issue of earthquake risk is not considered in engineering practice, nor are engineers educated in this field. On top of that, many younger engineers (affected by changes brought by Bologna process) did not even have, during their studies, courses such as structural dynamics, earthquake engineering, and engineering seismology! It is interesting to note that in February 2020 (a month before the earthquake) a proposal was made at the Faculty of Civil Engineering of the University of Zagreb to introduce postgraduate specialist study programme that would cover these issues, motivated by the fact that low level of knowledge was observed in this field. Considering the above mentioned, education of experts and also coordination was proven crucial – assembly of teams and schedule on site – taking into account the level of damage and importance of buildings.

During the first days after the earthquake, training sessions were organized at UHS premises, in form of discussions (Figure 12), in order to educate engineers so that they can properly inspect damaged buildings and estimate their usability, with emphasis on characteristic damages reported by citizens (chimneys, gable walls, roof structures, etc.). Afterwards, considering epidemiological requirements banning personal contacts, the training material was posted in digital format, together with appropriate webinars, at the internet site www.hcpi.hr (which was established very soon after the earthquake). The manual and webinars were inspired by the MATILDA project [36], numerous exercises [27, 37],

Figure 11. Filling-in the inspection form using *Collector for ArcGIS*

and especially by experience gained in the assessment of earthquake-damaged buildings in Albania in 2019 [33]. Training sessions were simultaneously conducted for the installation and use of *Collector for ArcGIS* application, for which appropriate instructions were also created. Taking into account potential problems, direct communication with engineers was realised within three *WhatsApp* groups that were initially conceived for communication between experts, i.e. for on-site consultation between inspectors (harmonisation of assessments), but also for directing questions to headquarters (to solve difficult issues). In addition, these groups were used to forward significant new information to engineers every morning. The already mentioned internet site www.hcpi.hr was used for providing information and as a database containing crucial information. This website was also used for informing citizens about building inspection procedures and about the meaning of each tag. This was especially important, because citizens often reported damage for the same address multiple times (each apartment for itself) or contradictory information appeared in media from various sources, and especially because of generally low level of knowledge about earthquake consequences (lack of awareness) and similar issues.

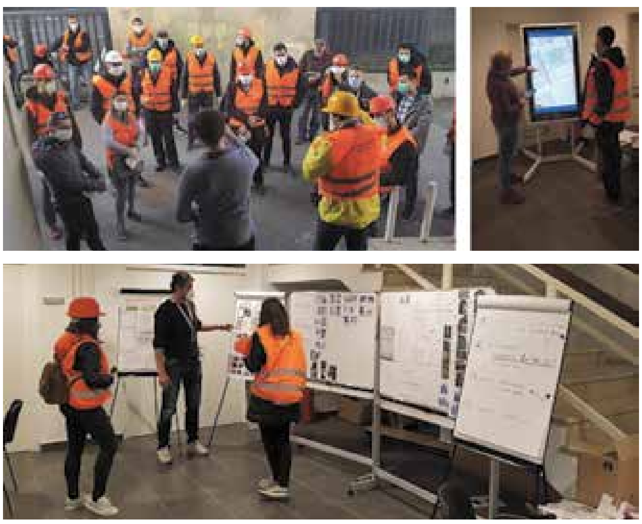


Figure 12. Training in Headquarters on building inspections

Rapid inspections of damage and usability of buildings were carried out for more than a month since the first damage reports submitted by citizens. Results singled out for 25 April 2020, report 10,357 buildings with green tag (U1 and U2), 3,342 buildings with yellow tag (PN1 and PN2) and 788 buildings with red tag (N1 and N2). Then the total number of inspected buildings was 14,487, and it should be noted that as many as 5,622 buildings were inspected in the first week only. The inspections were not officially terminated because the created database was the only feedback from field and so numerous national and municipal level decisions were based on it. That is why inspections became increasingly detailed and slower. For instance, in the early May the Government issued the *Decision on the provision of monetary assistance for the temporary and indispensable protection and repair of earthquake-damaged buildings in the area of Zagreb City and its surroundings* (Official Gazette 55/20) by which funds are provided for the indispensable temporary protection of buildings against the atmospheric influences or for removal/reinforcement of dangerous parts of buildings, and for the repair or replacement of chimneys, gable walls, and elevators, related to tags rom the existing database. In addition, in mid May the authorities issued the *Decision on financing rents for the accommodation of persons whose real estate suffered earthquake damage in the area of the City of Zagreb, Zagreb County, and Krapina-Zagorje County* (Official Gazette 57/20)*,* concerning persons whose buildings were red-tagged during inspections. In the late May the City of Zagreb issued the decision by which it donates construction material necessary for urgent repairs and introduces numerous benefits related to the transport, parking, utility costs etc., and all that relied mostly on the created and designed database. A special problem was a great number of damaged chimneys (about 5,300) which is why gas supply had to be temporarily disconnected. However, later on the question arose on who would assume responsibility, i.e. issue a certificate on the serviceability of outdated masonry chimneys and atmospheric gas-powered water heaters that are no longer installed. Finally, it is important to note that the database was also used for the first preliminary estimate of damage and reconstruction costs, which was an indispensable information for passing the *Law on Reconstruction of Earthquake Damaged Buildings*. According to this preliminary damage estimate, the total damage amounted to approximately € 1.2 billion and, between 7 provided reconstruction alternatives, the decision was made to select the "mean" one estimated at € 5.6 billion. An estimate is currently being prepared according to the World Bank methodology that is also based on this same database, but includes the BBB (Build Back Better) principle, so that it is assumed that the reconstruction costs will run in excess of € 10 billion.

Considering all the needs and the fact that the initial initiative was aimed at helping fellow citizens, the inspections were continued and, at the same time, numerous problems were addressed to such as additional damage caused by aftershocks, missed (or additional) reports, data updating (urgent measures executed), correction of

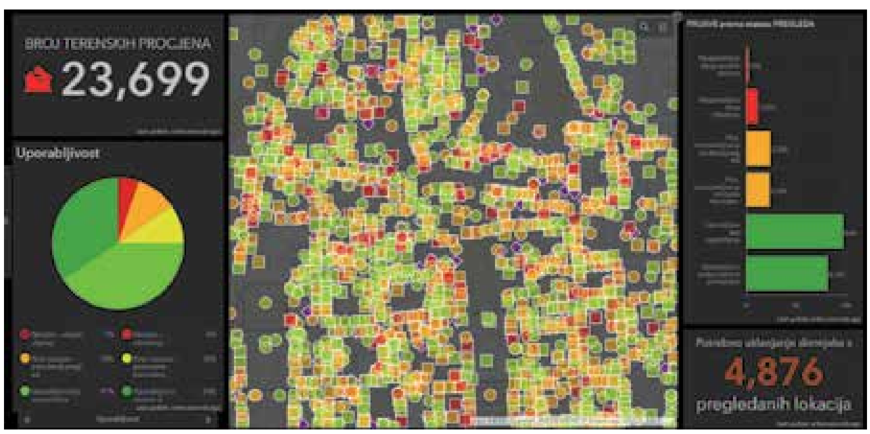


Figure 13. Statistics of inspected buildings according to the level of damage and usability of buildings after earthquake, situation on 8 June 2020

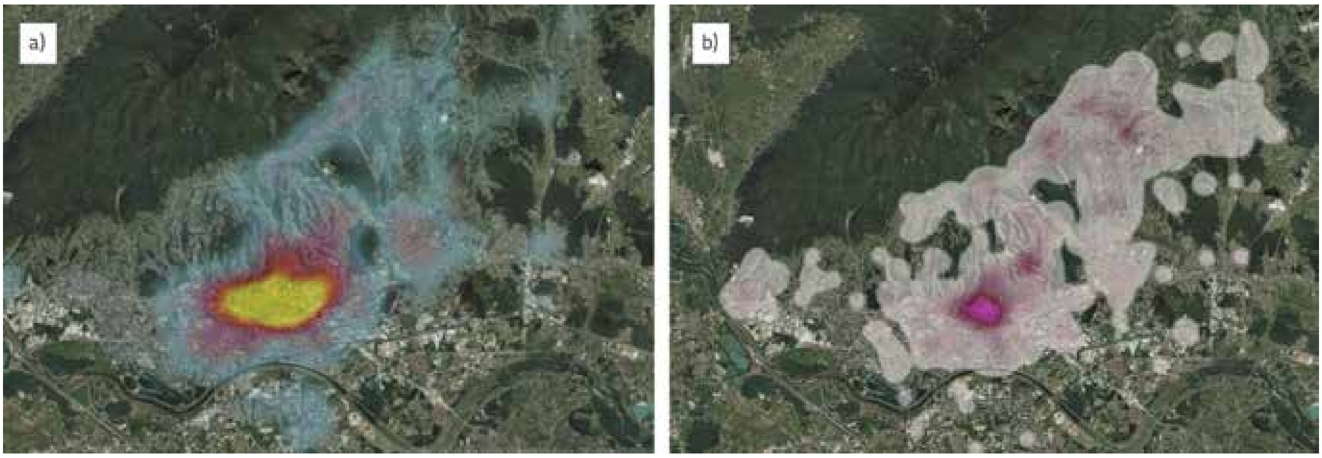


Figure 14. Heatmap of: a) building damage reported by citizens; b) unusable buildings (N1 and N2)

mistakes in the database, etc. (Figures 13 and 14). However, it is important to emphasize that the initial idea of inspections was to increase the safety of citizens, which is why the use of this database beyond this scope presents hidden dangers, particularly with regard to decisions about allocation of considerable financial aid.

Finally, the inspections were officially ended three months after the earthquake. As many as 25,528 inspections were performed (some buildings were inspected several times), and the total number of damage cases reported by citizens exceeded 42,163 (on many occasions the same damage was reported several times). According to results obtained until 30 June 2020, 19,188 (about 75 %) of buildings bear the green tag (U1 = 10,309 and U2 = 8,879), 4,998 (about 20 %) of buildings bear the yellow tag (PN1 = 2,585 and PN2 = 2,413), while 1,342 of buildings (about 5 %) bear the red tag (N1 = 178 and N2 = 1,164). By this official end of inspections, the database was closed, and only ten or so teams were engaged for additional activities.

In any case, a special recognition of the entire community must be given to all experts who contributed, through their selfless dedication, to the safety of their fellow citizens. The Faculty of Civil Engineering of the University of Zagreb initiated organisation of the system and, in order to assist fellow citizens, the Faculty put at the disposal of the community many of its employees (43 in total), which could have been expected considering their experience and knowledge gained through the previously mentioned projects and exercises. However, it should be noted that the key aspect was the support and cooperation of numerous institutions, companies and individuals, primarily of the Emergency Management Office, the GDI d.o.o. company, the Croatian Chamber of Civil Engineers, the Croatian Chamber of Architects, the Office for Strategic Planning and Development of the City, the Civil Protection Directorate of the Ministry of the Interior, the Zagreb City Office for Physical Planning, Construction of the City, Civil Engineering, Utility Services and Transport, the Croatian Association of Court Expert Witnesses and Valuers, the Faculty of Science of the University of Zagreb – Department of Geophysics and Seismological Survey, the Croatian Ministry of Construction and Physical Planning, the National Inspectorate of the Republic of Croatia, the Croatian Crisis Management Association, the University Computing Centre of the University of Zagreb, numerous colleagues from Split, Osijek, Rijeka and other parts of Croatia, and colleagues from Slovenia, Serbia, Italy, Switzerland, North Macedonia and Canada.

It is significant to note that the Ministry of Culture also conducted detailed inspections of cultural assets, using special forms, and the Croatian government in urgent procedure issued the *Decision on the implementation of the inventory of damage to immovable cultural assets* in early April and, soon thereafter, a similar decision for movable cultural assets. Finally, official damage assessments must be done, as stipulated in the existing *Act on Mitigation and elimination of consequences of natural disasters* (Official Gazette 16/2019) and the corresponding *Ordinance on the register of damage due to natural disasters* (Official gazette 65/2019). The assessments started about three months after the earthquake in part taking over the organisation and experts that took part in rapid inspections. Numerous problems and uncertainties exist in regard to these assessments, as the specified methodology is not harmonized with earthquake damage at all, which is mainly the consequence of the lack of awareness about seismic risk. Considering the current rate of activities, it may be expected that this assessment activity will soon be abandoned.

5. Observed damage according to preliminary field data

5.1. Typology of buildings in Zagreb area with emphasis on most commn types that were damaged in the earthquake

In the seismic risk assessment [3], the residential building stock in Zagreb was classified in detail according to structural systems at the level of local board districts. Fourteen frequent building types were identified, which comprise unreinforced masonry buildings, buildings with reinforced concrete walls, concrete frame buildings with infills and confined masonry, large panel reinforced concrete buildings (the so called "can-shaped buildings"), and reinforced concrete mid and high rise buildings [27]. As earthquake damage was mostly registered in older unreinforced masonry buildings with timber floor structures (the most frequent system, although there are others with vaults, reinforced-concrete slabs at some floors, etc.) situated in the old city core, and family houses (mostly of low quality masonry or without tie beams) located in the vicinity of the epicentral area, the focus in this paper will be placed on these building types. Structural systems of specific buildings, such as sacral buildings, will not be described in the paper. A residential building with plan view as shown in Figure 15 is a typical example of construction practices prevailing in the early twentieth century in Down town centre (Donji Grad). It was built in 1920 and it has a basement, elevated ground floor, three floors above it, and an attic. Plan view dimensions are 24.40 × 12.0 m (street side) and 10.6 × 12.0 m (courtyard side), and the total gross plan view area is 396 m². The building is 22.70 m in height. The attic was initially not meant for habitation, but it was transformed during one of renovations and converted into a residential space. The structure is made of a system of interconnected solid brick walls, without tie beams, which continuously run from foundations to the roof. The external and internal load bearing walls of the ground floor and other floors are made of solid brick of old format, 30, 45 and 60 cm thick, while partition walls are made of solid 15 cm thick brick, with obviously uneven distribution of stiffness. The area of ground floor walls is about 8.0 % of the gross floor area in the longitudinal direction and 9.35 % in the transverse direction. On the first floor it is 6.8 % of the gross floor area in both directions. Basement walls are 60, 75 and 90 cm thick. Floor structure above basement is a reinforced concrete slab (otherwise, masonry vaults are often used instead of slabs), and timber joists oriented in transverse directions are situated above the ground floor and the floors above it (they are supported by longitudinal walls). The roof structure is made of timber. The building has an internal dog-legged staircase made of prefabricated elements supported by steel sections, with reinforced concrete landings.

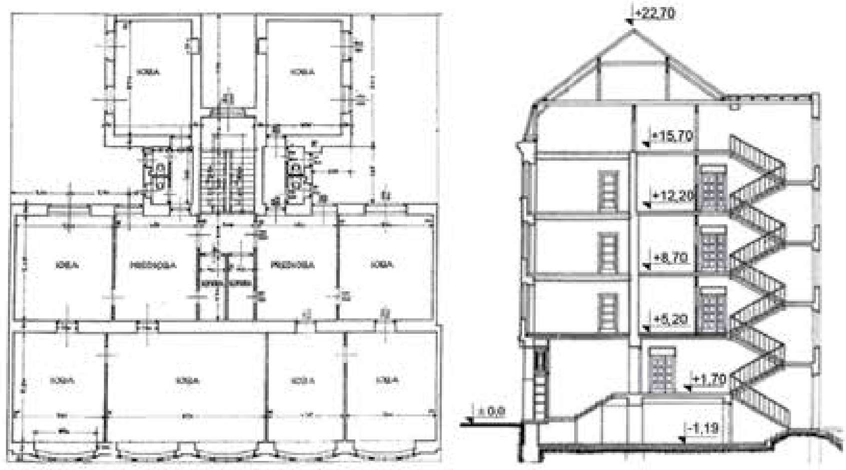


Figure 15. Plan view and cross section of a typical building in Donji Grad

It is important to emphasize that the buildings situated in the historic centre of the city are built in blocks, rather than as detached buildings, which additionally complicates the analysis of their seismic behaviour. In addition to the fact that these buildings are generally old, the problem also lies in their poor maintenance, and in subsequent alterations and additions. For instance, during renovations of individual housing units, builders very often remove walls without understanding the concept of load bearing structures, and replace them by steel beams or reinforced-concrete frames. Structural analysis, if performed at all, usually takes into account only the vertical loads, while the analysis of horizontal loads (for example analysis of seismic resistance of the building) is avoided as it requires more complex calculations, additional funding, and as it is very difficult to prove building load-bearing capacity according to prevailing standards. Very often the designers try to make use of a provision contained in *Technical regulation for structures* "proving" that the change of structural properties of the building is less than 10 %. In effect, this provision is very often misused, as it enables renovation of a housing unit without proving mechanical resistance and stability of the building according to present structural standards. It is interesting that builders/designers are not obliged to document such renovations in individual cases (and database of such renovations is not created), so that it may happen that during an extended period of time most housing units in a building undergo renovation (adjustment to new styles of living) which may greatly weaken the load-bearing structure of the entire building. In addition, interventions in older apartments often involve removal of walls of smaller thickness, as they are considered non-bearing according to standard practice based on recent layouts. Unfortunately, such interventions result in external walls not being supported out of their plane, which is inadequate for seismic action, especially considering their height. Furthermore, in traditional construction, partition walls are usually extended along the height (thus transferring load), which in case of inadequate support during construction of replacement beams or frames fairly often causes opening of cracks in floor slabs [33]. Such numerous cracks and documents that do not correspond to the current condition of the building (such as significant differences with regard to original documents from city archives) have greatly confused experts during the post-earthquake building assessments of damage and usability.

As for family houses situated in the vicinity of the epicentral area, it is important to mention the *Law on the treatment of illegally constructed buildings* which has enabled legalisation of buildings in such a way that fulfilment of basic requirements regarding mechanical resistance and stability is reduced to issuing of certificates by the designer, who usually had minimum knowledge about properties of the load bearing structure. Over one hundred thousand legalisation requests have been received in Zagreb only, and the question of safety of such buildings has never been raised outside the professional community. During inspection of buildings, numerous examples have been found of the so called mixed systems based on the "do it yourself" principle and, here, we would like to describe one usual (typical) example of a building with damage. It is a house measuring about 100 m² in plan, comprising basement, ground floor, first floor and attic (not used for habitation). The structure is formed of load bearing walls 25 cm in thickness made of solid brick (unfortunately) without tie beams (unconfined walls), and the floor structure is a timber joist or semi precast reinforced-concrete floor structure with load bearing capability in one direction (the so called "FERT floor structure"). Roof structures are usually made of timber, they are double-pitched, while foundations are made of concrete (without reinforcement). In this particular case, the initially poor structural system was further weakened by additions and renovations, as can be seen on other similar structural systems. Very often, addition of one or more floors is subsequently made without strengthening the ground floor, although in new floors we may find walls with tie beams (not extended to the ground floor). On top of that, board based floor with rubble is often removed during renovation and replaced with concrete slab without reinforcement, and without adequate anchoring into walls.

5.2. Typical damage

5.2.1. Introduction

Traditional masonry buildings were most often built as systems of interconnected load bearing walls with timber floor structures. In case of an earthquake, they are mostly damaged because of uneven distribution of stiffness, inadequate or nonexistent interconnections, and poor contact with roof and floor structures (they are very flexible and so walls may deflect out of their plane). An obvious deficiency is the lack of confining elements (vertical and horizontal tie beams), poor bearing capacity in their own plane, and insufficient bearing capacity of roof and floor structures, which causes additional damage. Because of long service life of buildings, poor maintenance, and lack of facade at some external walls (such as gable walls), the material deteriorates quite rapidly thus increasing inhomogeneity of walls and loss of binding material.

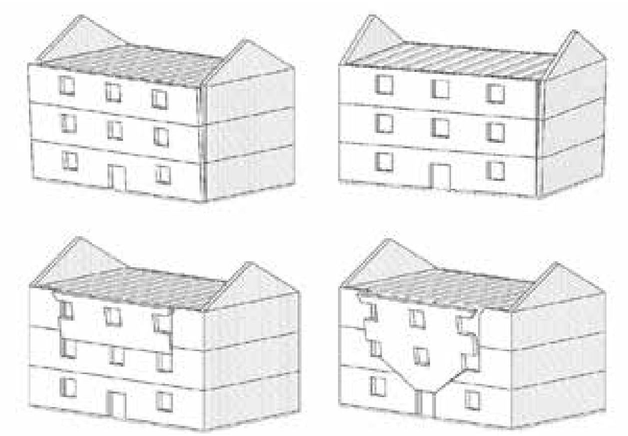


Figure 16. Out of plane inclination of walls

Damage most frequently suffered by old masonry buildings situated in the central part of the city involves collapse of chimneys, gable walls at attic level, and other cantilever parts at the top of the building (parapets, various cantilevers, etc.), and damage to roof structure. In rare cases, gable wall detached from the building along the entire height of the building, and sometimes the facade wall collapse was also registered. Leaning of walls caused detachment of floor structures, and extraction of joists from their supports.

In addition to out-of-plane wall failure mechanisms (Figure 16), many buildings were affected by formation of diagonal cracks in load bearing (structural) and non-bearing (non-structural) walls and lintels due the exceedance of in-plane bearing capacity . Some photographs of frequent damage, sent by experts conducting on-site inspections, are presented below.

5.2.2. Damage and collapse of chimneys

Frequent damage was incurred on roof structures and attics due to partial or full collapse of attic level chimneys (Figures 17 and 18). These chimneys were originally made of brick and mortar and are therefore not resistant to horizontal actions. They were often built as free-standing structures from the attic floor and sometimes reached more than 5 m in height, and only in rare cases are they supported by roof structure. Chimneys mostly suffered damage at the connection to the roof structure or at the attic floor level at the connection with the floor structure [38].

5.2.3. Damage and collapse of attic gable walls

Other than chimneys, the most frequent damage is either partial or total collapse of attic level gable walls (Figure 17.c). These walls are often 15 cm thick and are not adequately fixed to the roof structure. They are mostly constructed as unreinforced masonry without out-of-plane stabilisation. Beside attic level gable walls, some buildings also suffered damage by collapse of unrestrained walls perpendicular to gable walls (i.e. longitudinal walls of the front and back facades) [38]. An additional weakness is that walls were usually not properly restrained at floor levels. Timber beams lean onto grooves in the longitudinal walls, they are spaced at approximately 80 cm, and are not structurally linked with the wall.

5.2.4. Detachment of gable walls

In addition to local collapse of attic gable walls, in more difficult cases the damage involved detachment of gable walls along the entire height or through several floors (Figure 19). The reason is poor connection with walls from the other direction.

Figure 17. Collapse of chimneys and top part of the gable walls (photo courtesy of Mario Todorić and [39])

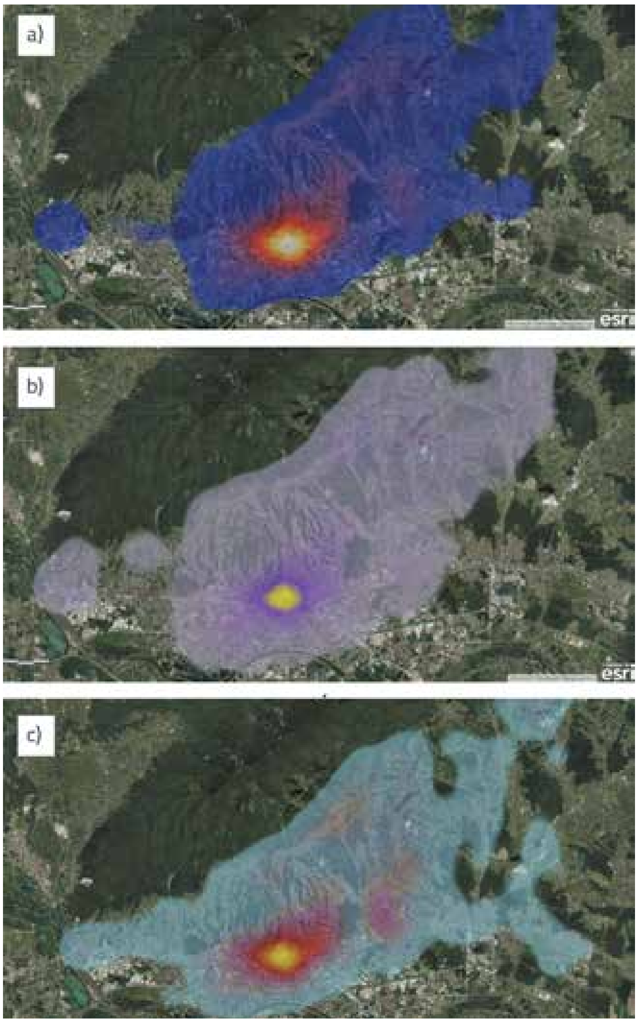


Figure 18. Heatmaps of: a) damaged and collapsed chimneys – data obtained from citizens by survey via *Survey for ArcGIS*; b) damage of gable walls and roofs from the database of on-site damage and usability inspections; c) interventions made for damaged and collapsed chimneys – data obtained from Public Fire Brigade of the City of Zagreb, last time updated on 5 May 2020

Figure 19. Detachment of gable wall and typical cracks in internal part of the building (photos courtesy of Mario Todorić and **[39]**)

We have already pointed out that gable walls are usually not restrained, because they are not connected with floor structure, which is formed of timber joists leaning onto longitudinal walls, nor are they adequately connected with the roof structure. That is why gable walls have small vertical load, which contributes to poor load-bearing resistance to horizontal loads. Such gable wall detachment results in characteristic vertical cracks in orthogonal wall and in horizontal cracks on ceilings, mostly at the connection between floor structures and gable wall. More pronounced detachment may lead to wall overturning and constitutes a great hazard for the structure and people near the building.

5.2.5. Damage to roof structure

We have pointed out that the most frequent cause of damage to roof structure is the collapse of chimneys, gable walls and other unsupported elements above the roof plane. This is mostly local damage to the roof structure (Figure 20). However, it should be noted that roof structures are usually not adequately stabilised, and due to lack of maintenance and old-age they are additionally unsafe and cannot restrain chimneys and attic gable walls [38]. In some cases, involving flexible roof structures, permanent displacements of the entire roof structure were registered, which is extremely dangerous and requires full reconstruction.

Figure 20. Roof structure damage (photos courtesy of Mario Todorić)

5.2.6. Damage to other cantilever elements (parapets, attics, consoles and decorative elements)

Elements of building heritage, such as roof domes, portals, cornices on facades, and decorative sculptures, have also suffered considerable damage (Figure 21). These elements represented and still represent considerable hazard in case of an earthquake event [38]. As these elements are mostly made of brick or concrete, they may inflict considerable damage when falling from large height. It is interesting to note that Andrija Mohorovičić stated already at the beginning of the twentieth century that these elements should either be properly stabilised or altogether removed precisely because they could present danger in case of an earthquake.

Figure 21. Damage of decorative elements (photos courtesy of Mario Todorić and **[39]**)

Figure 22. Diagonal cracks in load bearing walls [39]

Figure 23. Lintel damage: diagonal and vertical cracks [39]

5.2.7. Typical in-plane wall damage

In addition to out-of-plane wall failure mechanisms, cracking due to insufficient load bearing capacity of walls in their own plane was also quite frequent. These cracks are most often diagonal and are caused by exceedance of shear strength (Figure 22). Such failure mechanism often occurs is usually accompanied by a crack at joints due to poor quality of mortar which lost its mechanical properties over time.

5.2.8. Damage to lintels and vaults

Lintel cracking is one of the most frequent forms of damage (Figure 23). It is typical for masonry and reinforced-concrete buildings. Diagonal cracks at lintels can very often be seen even in recently built buildings. If cracks are not wide, they do not necessarily present hazard, although sometimes complete failure with fall of material occurred in case of masonry lintels. They are particularly susceptible to damage and must be protected against collapse. Diagonal cracks in lintels usually mean that the shear strength has been exceeded, while approximately vertical cracks are attributed to tensile strength being exceeded.

5.2.9. Partition walls

In addition to gable walls, within floors there often exist mutually parallel partition walls 15 cm or even only 7 cm thick. In case of larger horizontal actions such walls participate little to overall building stiffness, they are often not regularly arranged by height (consequence of numerous subsequent interventions), and they lean on timber joists. Furthermore, due to their small resistance and significant initial stiffness, they cannot follow displacements of the entire structure and regularly crack. In the centre of the city, there are many partition walls that suffered damage in the direction perpendicular to the facade wall.

5.2.10. Cracks in ceilings (floor structures)

Small cracks in the direction of joists most often occurred because of displacements due to bending between beams. Such cracks rarely occur due to tensile forces perpendicular to joist. Cracking is often pronounced along the connection between the wall and the floor structure, which is due to relative displacement between these elements. Generally, if the wall does not detach and lean, only the plaster is usually affected, Figure 24.

Figure 24. Cracks at ceilings [39]

Figure 25. Cases of staircase damage [39]

5.2.11. Damage to staircases

Staircases often suffer damage in older masonry buildings (Figure 25). In most cases, the damage is either structural or involves separation of elements. Staircases are often supported by steel girders, anchored into landings. Around staircases there is usually a relatively stiff core comprising thick masonry walls.

5.3. Residential and commercial-residential buildings

Although cultural heritage and some public buildings have suffered considerable damage, as will be described in the following section, largest damage was still incurred by the housing stock. Results obtained by inspection of usability of residential and commercial-residential buildings are shown in Figure 26, where colours correspond to usability tag, while column heights indicate the gross floor area of buildings. It can be observed that the greatest damage was inflicted on historic centre of the city, which is why we will present below some data about the Down Town (Donji Grad) and a typical building block, as well as photographs of typical damage to houses situated near the epicentre.

According to the data provided by the Institute for Physical Planning of the City of Zagreb, the total plan view area of all buildings in Down Town amounts to approximately 1,150,00 m^2, and most housing blocks occupy between 40 % and 60 % of their plots. The total gross built-up area in Down Town amounts to approximately 5,200,000 m^2. The average number of building storeys is 5 (GF+4) [40]. Figure 27 shows a city block occupying an area of 15,741 m^2, with the gross floor area of buildings amounting to 40,024 m^2, and with averagely 4 storeys. The occupancy is mixed, but mostly residential.

Twenty-seven buildings were inspected in the selected building block. Four of the buildings were given a green tag U1 (usable without limitations), eleven a green tag U2 (usable but with recommendation), two a yellow tag PN1 (temporarily unusable, detailed inspection needed), six a yellow tag PN2 (temporarily unusable, urgent interventions needed), two red tag N1 (unusable due to external risks), and two a red tag N2 (unusable due to damage). After reviewing the assessment forms, the following may be concluded:

- buildings classified as U1 mostly suffered insignificant damage of the roof structure and exhibited some cracks (small in width and length) in structural and non-structural walls, dominantly around staircases;
- in almost all buildings classified as U2 masonry chimneys were damaged or even collapsed (which presented a hazard

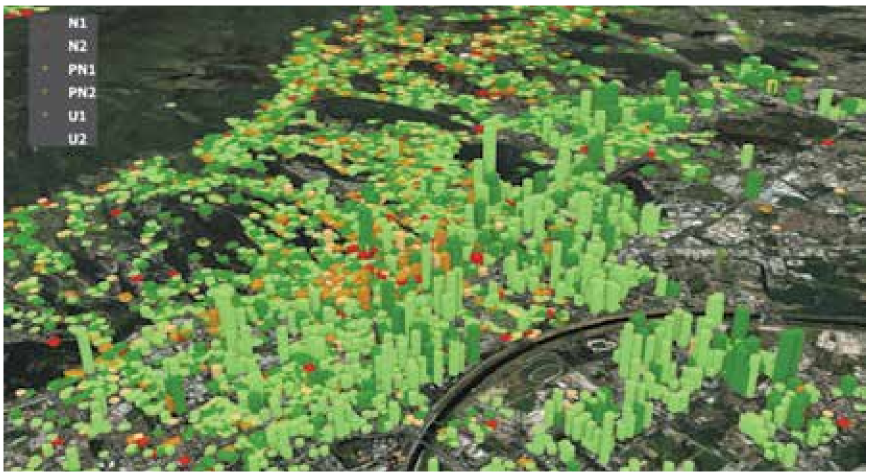


Figure 26. Damage to residential and commercial-residential buildings according to usability tags (colours) and gross floor area of buildings (height of columns) on a perspective view of the city of Zagreb

Figure 27. Example of a block selected in Down Town area

for citizens); damage sometimes included partly collapsed top parts of gable walls, smaller cracks in lintels and some load bearing walls, and damage to partition walls;
- buildings classified as PN1 exhibited moderate to significant damage of structural and non-structural elements, especially at staircases, and heavy damage to the roof structure due to chimneys' collapse. By accelerated inspections it was not possible to assess damage influence on the building load-bearing capacity, and so a detailed inspection was advised;
- buildings classified as PN2 exhibited considerable damage to gable walls, heavy damage to the roof structure due to chimneys' collapse; top floors are often unusable, with imminent collapse hazard;
- in buildings classified as N1 there exists mostly danger of the gable wall collapse (or of other unsupported elements) from a neighbouring house;
- buildings classified as N2 exhibited considerable and heavy damage to structural elements, mostly in staircase area (which makes them dangerous in case of evacuation), then heavy damage to the roof structure due to chimneys' collapse, and considerable detachments and collapses of gable walls.

Figures 28 and 29 show frequent damage to houses near the epicentral area. As already pointed out, these are mostly masonry houses without tie beams, but various mixed systems were also encountered because old single storey houses were often subsequently raised by adding a floor.

Figure 28. Damage to houses at LB Vidovec, CD Podsljeme (photo courtesy of Luka Božić and **[39]**)

Figure 29. Damage to houses at LB Dankovec, CD Gornja Dubrava (photo courtesy of Luka Božić and **[39]**)

5.4. Public buildings

The earthquake caused damage to many significant buildings such as hospitals (for instance, Lung Disease Hospital – Jordanovac, Clinic for Women's Health and Obstetrics – Petrova, Children's Hospital – Klaićeva, and Šalata clinics), numerous schools and kindergartens, university buildings, 28 faculty buildings and three academy buildings (hardest hit were the buildings of the Faculty of Law, the Faculty of Medicine, and the Academy of Fine Arts), high school and university student dormitories, sacral buildings (such as Zagreb Cathedral and Archbishop's Palace, Basilica of the Sacred Hearth of Jesus – Palmotićeva, St Catherine Church in the Upper Town, Church of the Assumption of the Blessed Virgin Mary – Remete), Croatian Parliament building, judicial buildings (Supreme Court and County Court buildings), museums (such as the Archaeological Museum, Museum for Arts and Crafts, Croatian School Museum, Croatian Science Museum, Art Pavilion), theatre buildings (such as Gavella Theatre building, Komedija Theatre building), palace and library of the Croatian Academy of Sciences and Arts, and many other notable buildings. It should be emphasized that, according to the latest processed data from inspections, two hospitals, three faculty buildings, one kindergarten, four schools, six cultural institutions

Figure 30. Earthquake damage to some notable buildings: Mirogoj Cemetery (a.-d.), Franciscan Monastery at Kaptol (e), registry office building of the Faculty of Medicine at Šalata (f.-g.), University and Faculty of Law building (h.-i.) [39]

and fifteen sacral buildings have been marked as unusable, while many other significant buildings have been marked as temporarily unusable (over 200 of them, including only the buildings from the above mentioned categories). Some damages to these notable buildings are shown in Figure 30.

As already stated, the earthquake inflicted enormous damage to buildings belonging to the protected architectural heritage. These are highly valuable private and public sector buildings of various occupancy types, which represent cultural landmarks of the City of Zagreb (Table 1, Figure 31). The damage was mostly inflicted to gable walls and roof structures with chimneys. There follows internal damage to structural elements, mostly vaults, lintels and, less often load bearing walls, mostly at connection with flexible timber floor structures.

Table 1. Number of damaged individual heritage buildings in various sectors, according to usability category

Number of damaged individual heritage buildings	City of Zagreb		
	U1 & U2	PN1 & PN2	N1 & N2
Culture-related buildings	21	10	6
Churches and chapels	7	15	8
Other sacral buildings	6	10	4
Educational and scientific institutions	27	29	1
Healthcare buildings	7	4	0
Other private and public buildings	192	94	30
Total	**260**	**162**	**49**

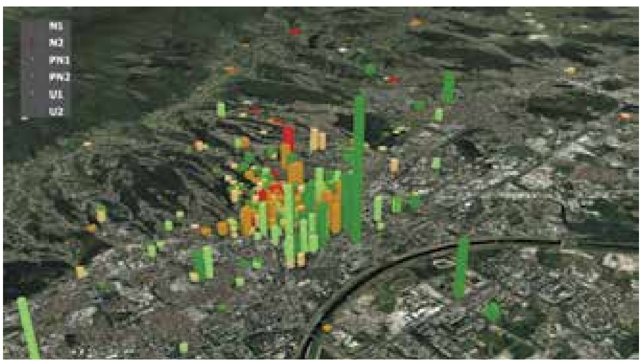


Figure 31. Damage to cultural heritage buildings according to usability tags (colours) and gross floor area (columns) on 3D arial view of the City of Zagreb

Figure 32. Damage to the cathedral's parish house and the St Mary's Church (source: Ministry of Culture of the Republic of Croatia and **[39]**)

As to cultural heritage buildings, the greatest damage was inflicted on numerous centuries-old churches (cf. Figures 32-34). Out of the total of 43 churches that suffered damage in the city, 30 of them belong to the category of protected cultural monuments. The stone top of the south belltower of Zagreb Cathedral, Croatia's largest sacral building, detached from the base and fell onto and damaged the roof structure of the cathedral. After inspection, it was established that the north belltower also suffered considerable damage, which is why the potentially harmful part had to be removed as it could have fallen onto the cathedral. In addition to the belltower, the balustrade above the apse also collapsed, and great damage was inflicted on facade walls and vaults of this cathedral. Considerable damage to vaults and roofing was also incurred at the cathedral's Archbishop's Palace, where chimneys also collapsed.

Figure 33. Damage to Basilica of the Sacred Heart of Jesus (photos courtesy of: Ivan Ćurić)

Figure 34. Damage to Church of the Assumption of the Blessed Virgin Mary at Remete and damage to a statue in St. Catherine of Alexandria Church (source: Ministry of Culture of the Republic of Croatia)

The St Mark the Evangelist's Church, dating back to 15th century, suffered extensive damage to gable walls that partly detached from the building, as well as damage to facade walls, stone lintels, load bearing walls and vaults. In the Basilica of the Sacred Heart of Jesus in Palmotićeva street almost one third of the ceiling collapsed. Significant damage was inflicted on St. Catherine of Alexandria Church, St Mary's Church at Dolac, Church of the Assumption of the Blessed Virgin Mary at Remete (Figure 34), Church of the Holy Transfiguration, Church of the Visitation of the Blessed Virgin Mary at Čučerje, Church of the Nativity of the Blessed Virgin Mary at Granešina, and many others. It should be noted that, in addition to damage to structural elements, significant damage was registered in decorative elements such as frescoes, valuable pargeting, sculptures, marble altars and stained glass windows. It is currently impossible to estimate how long will the structural reconstruction of these churches last, because the works will have to be carried out in accordance with appropriate conservation-restoration requirements.

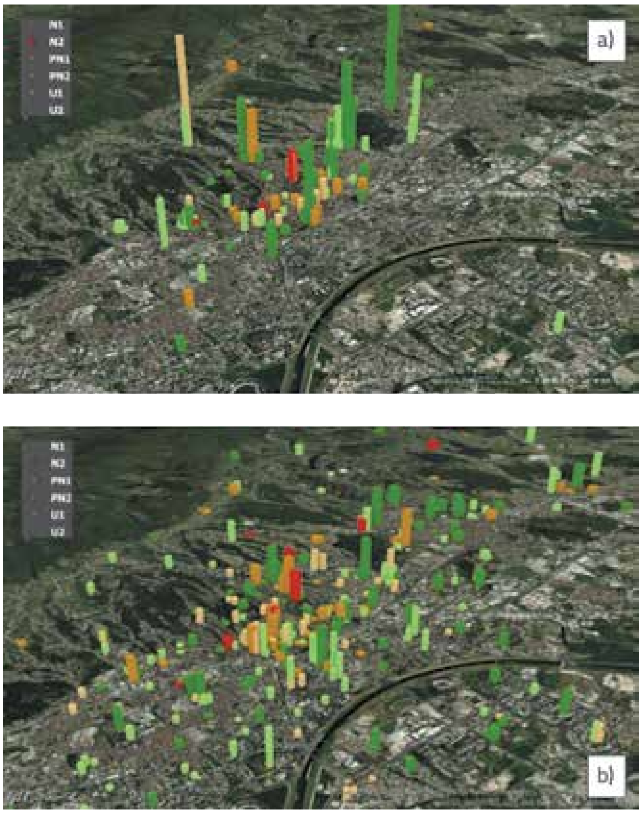


Figure 35. Damage to buildings according to usability tags (colours) and gross floor area (columns) on 3D arial view of the City of Zagreb for the sectors of a) healthcare and b) education

Damage assessments of critical infrastructure (hospitals, schools, faculties, and kindergartens) are shown in Figure 35 according to the level of damage (colour) and gross area (column height). A detailed presentation of two examples of damage to hospitals is given below.

Clinic for Women's Health and Obstetrics – Old building

Zagreb residents will remember a long time distressing scenes of pregnant women and babies that were urgently evacuated after the earthquake from the hospital building. Rapid visual inspection of the building's structure was conducted immediately after the earthquake. The main old building was inspected, as it is in the most critical, considering that it dates back to the early twentieth century. It is irregular in plan, and it comprises masonry walls of solid brick of old format. The building comprises the basement, the ground floor, two floors above it, and the attic. Floor structures in room areas are timber joists, while masonry vaults are used in corridors.

Some chimneys collapsed in the earthquake so that the heating system had to be shut down, the gas supply turned off and he hot water supply cut-off. The inspection has revealed damage to staircases that lie along the edges of the east and west parts of the building. Over time, some improper changes and reconstructions were made, which cracked, although this cracking did not affect the overall load bearing capacity of the building. Besides these damages, cracking of the attic overhang and of the cornice was detected, which could imperil the area in front of the main entrance in case of another earthquake, and so the recommendation was given to limit the access to hospital from the front side, and to use the alternative entrance. The system of cracks spreading along the entire building was identified, but these cracks do not pose danger to the bearing capacity and serviceability of the building. Diagonal cracks were observed at some spots along short walls, but they are of local character only. Although a detailed inspection of floor structures was not possible, significant damage and wider cracks were not identified at the connection with walls. However, local detachment of plaster, non-bearing parts of the structure, equipment, and installations, was locally observed. Structural damage to vaults was observed at the ground floor and first floor of the west wing of the building. Based on rapid visual inspection of the structure, it was established that the central and east parts of the building can safely be used (once the heating is restored). The use of west wing, and access to and passage around the building are temporarily limited, due to possible falling-off of roof windows, roof tiles and parts of the roof cornice. The situation after the earthquake is presented in Figure 36.

Figure 36. Damage to the Old building of Clinic for Women's Health and Obstetrics in Petrova

Building of Orthopaedics Clinic on Šalata

The building of Orthopaedics Clinic at Šalata was built in 1931. It is of elongated rectangular form in plan, and is composed of the central part with the main entrance, and the west and east wings that are symmetric to one another. The building measures 17 x 60 meters in plan. Basement walls are built of concrete, while walls above the ground level are built of solid brick of old format. They differ in thickness and run in longitudinal and transverse directions, interconnected with reinforced concrete floor structures. The clinic consists of the basement, the ground floor, and three floors above it. Partition walls are also built of solid brick. Even before the earthquake, the building was poorly maintained, as evidenced by brick facade walls, which were severely exposed to atmospheric influences, as much of the plaster had fallen off. Tops of both chimneys at the west side of the building collapsed as a result of the earthquake (Figure 37). One chimney separated by approximately ten centimetres from the facade wall, viewed from the roof level, and it now represents a considerable hazard for hospital staff and patients. Urgent removal or reinforcement at the RC slab levels was recommended. The inspection has revealed significant damage to many load-bearing and partition walls. The damage is especially pronounced in east wing walls, where it spreads all the way from the ground floor to the attic. Mostly affected are transverse walls where pronounced diagonal cracks, spreading across most of the walls, were observed. At the central part of the building, load-bearing walls are less damaged. Cracks observed at some locations point to shear failure of walls. Partition walls made of solid brick are generally quite damaged with pronounced diagonal cracks.

Figure 37. View of damage to building of Orthopaedics Clinic

Based on the above damage, the following conclusions can be made:

- Individual floors of the building are in poor condition and are considered unsafe for staff and patients.
- The only place that can be used (with caution) is the basement, where no significant damage has been observed. A favourable action of the RC slab at basement level may be noted, because even in case of partial collapse of the wall at one of the above-the-ground storeys, the basement level would not be affected.
- To ensure safe use of the basement, other remedial activities must be performed so as to prevent detachment and fall of chimneys parts, plaster, roof elements, and other poorly attached objects situated at elevated points. This primarily concerns elimination of possible hazards at the basement entrance from the north side of the building, which is operated via a closed ramp.

6. Reconstruction

The *Law on reconstruction of earthquake-damaged buildings,* which is to assist in speedier recovery of the community affected by this seismic event, was at the stage of public consultations at the time this paper was drafted (May-June 2020). Once adopted, this law should specify the method and procedure for the reconstruction of damaged buildings, possible removal of unusable family houses and construction of replacement family houses, appointment of competent bodies, practical operating procedures. etc. Four reconstruction levels are proposed, depending on the building occupancy and level of damage, which is currently described in great detail in technical guidelines that are an appendix to this Law. The possibility of integration of these guidelines into a technical regulation is currently being considered. They were prepared by some thirty experts, most of them designers of masonry structures with considerable experience in complex designs of reconstruction of various buildings, and the core of the working group is formed of experts who focus, in their research and professional work, on various earthquake engineering issues and seismic risk analysis. Two months after the earthquake the engineers also proposed a manual called *Urgent programme for seismic reconstruction* – UPPO [38], where structural engineering solutions for implementation of urgent remedial activities of earthquake damage, in order to protect buildings from further propagation of damage and to ensure minimum conditions for their safe use, are presented. It may be concluded that this *Urgent Programme* covered the first level of reconstruction, and other manuals covering the remaining levels are currently being prepared. One of key objectives of the guidelines it to avoid reconstruction of buildings damaged in this earthquake, still of moderate magnitude, by repeating poor construction details initially applied in these buildings, but rather to improve their long-term resistance (based on the Build Back Better principle) to some future earthquakes using relatively simple procedures, without generating considerable indirect costs and without requiring moving out of persons living in such buildings. An attempt was made to make a step forward by raising awareness of citizens and competent authorities about the fact that the resistance of the damaged buildings had been very low even before the earthquake and that it is practically impossible to raise their resistance (at reasonable cost) to the level required by the standards that are currently applied for new buildings. In other words, full safety can be guaranteed only by implementation of complex and expensive remedial activities, which would not be cost-effective and/or technically feasible for most of the earthquake-damaged buildings. In addition, cultural value of most buildings situated in the centre of the city should also be taken into account, as their historic significance might be reduced through implementation of complex remedial activities. Taking all this into account, and aiming to ensure technical correctness and cost effectiveness of remedial activities, while also taking into account already mentioned problems currently faced in Croatia, an attempt was made through these guidelines to define an optimum approach to this many-faceted problem. As a sort of protection of the profession, each building would be provided with a seismic certificate depending on the reconstruction level, and proven mechanical resistance and stability for a particular level of seismic action. This certificate would raise the awareness of owners on the safety level of their real estate, while also motivating them to make long-term plans how to adequately manage it.

7. Future seismic risk mitigation advances

The earthquake that hit Zagreb and its surroundings in the spring of 2020 has unfortunately drawn attention to all problems that the Republic of Croatia is currently facing due to the lack of activities and strategies aimed at mitigation of seismic risks. It is crucial to understand this earthquake as a warning, i.e. as an opportunity to take action, because the magnitude of this earthquake was much lower compared to the one that could have been expected. Therefore, potential consequences of stronger future earthquakes, in accordance with tectonic potential of Medvednica and its surroundings, should be considered. Although warnings about possible catastrophic consequences of seismic action were given through official assessments of seismic risk, as well as through numerous conducted research activities, it is unfortunate that an earthquake had to happen for these warnings to be taken seriously.

We do hope that this earthquake has risen the level of general awareness and that it will now be easier to solve numerous problems we have been faced with in a systematic and all-encompassing manner, and that the long term strategy will be developed at the level of the Republic of Croatia, rather than at the level of currently hit regions only. The conclusions that follow are related to the paper [32] that was published a month before the earthquake, and in which the authors warned about numerous problems. These conclusions will be associated with consequences of the earthquake we experienced, so that similar errors are not repeated.

Conclusion 1: *"The earthquake risk is one of the greatest risks to Croatia taking into account the extent of consequences that are estimated through current risk assessments. Despite the fact that assessments can be more reliable if more detailed input data are provided (for instance, about the building stock), almost all these assessments point to the thousands of casualties, significant number of collapsed buildings, costs at the level of national budget, and similar effects (catastrophic consequences). Such levels of damage can ultimately put in jeopardy economic stability of the country and additionally increase current emigration of population, i.e. such damage can undermine social and political stability of the country (conclusions based on national risk assessments)."* – the above relates to the worst scenario that could happen in Zagreb and Croatia, and the damage incurred in this year's only moderate earthquake clearly points to these facts.

Conclusion 2: *"More reliable risk assessments are crucial for enacting quality strategies and, in Croatia, we have many problems (challenges) that we have to solve. Continuous investments in each element of risk are indispensable, emphasizing considerable densification of the seismographic and accelerographic networks and microzoning (to define of seismic hazard), creation of database containing structural properties of buildings (definition of exposure) and analysis of typical buildings (definition of vulnerability). In addition, it is of crucial significance that the results obtained by assessments and analyses do not remain a dead letter (aimed at addressing certain requirements or regulations in form only), i.e. they should be translated into concrete measures for risk reduction."* – unfortunately, the earthquake happened before realisation of the above activities (which are quite common in developed countries with high seismic risk), and so we should use this warning, the time that we have, and especially the knowledge and experience, to adequately devise the system and strategy for the future.

Conclusion 3: *"Implementation of measures for the reduction of earthquake risk (consequences) and preparedness of social community are of crucial significance. Measures are most often (and most easily) directed toward the change of regulations which should ensure that buildings are earthquake-resistant (such as regulations from 1964) and toward the adequate preparedness of emergency intervention services, which is at satisfactory level in Croatia. On the other hand, as a large-scale construction of a new housing stock is not expected in Croatia, quality strategy regarding the existing buildings (critical infrastructure buildings in particular) is crucial. Detailed analyses are required in the first step, because they may provide numerous useful data – such as those related to seismic strengthening (crucial measure that is not implemented in Croatia) or for assistance to emergency services. Measures (activities) that are currently implemented in Croatia are at a minimum level and are not related to one another, so that the burden rests on individuals, while, on the other hand, example of Italy can be cited with strategic investments of more than a billion euros over this decade"* – recent earthquake has also prompted retroactive writing of laws, manuals and numerous activities that have not been prepared in advance but, ultimately all that comes down to investment in crucial seismic strengthening, especially of critical infrastructure buildings (hospitals, schools, etc.), which is many times more cost-effective if done in advance.

Conclusion 4: *"Global research activities (such as those conducted in the scope of the Global Earthquake Model) are an opportunity for Croatia to catch up with the latest research and methodologies. Specific features of individual countries are difficult to take into account by global resolution, which is why contribution of national experts familiar with research achievements and with building traditions in the country, is invaluable. For instance, in Croatia one has to take into account massive illegal construction, numerous undocumented reconstructions, locally specific buildings, old-age and lack of maintenance of housing stock (including critical infrastructure buildings), etc. Establishing connection and cooperation with global initiatives makes possible knowledge transfer, and opens up numerous opportunities for investment by which some of the many challenges we are faced with can be resolved."* – establishing connections with global and European research activities should be encouraged, but it should also be pointed out that this is currently reduced to individual efforts of research institutions or individuals. What is lacking is the central connectivity of institutions within the country, as such synergy would prompt concrete application of research results.

Conclusion 5: *"Seismic risk awareness is a crucial factor as it permeates all segments of the society: from authorities that make strategic decisions (risk mitigation measures) to citizens who make decisions about how to build their homes (in accordance with prevailing regulations or through illegal interventions). The key emphasis must be placed on continuous work aimed at raising awareness, so that people can learn how to live with earthquake risk (for instance, like in Japan that is exposed to much greater earthquake hazard than Croatia), and include safety concerns regarding their real estate as integral component of their activities, and thus we would at least less miss opportunities that we can they can accomplish (some even without significant investments)."* – the task of raising awareness was accomplished by the earthquake itself, while the lack of awareness in the past period is the cause of extensive damage, which can be exemplified by a great number of reconstructed and poorly maintained buildings. It must not be allowed that awareness about the seismic hazard wears off just because collective memory lasts a relatively short time, so that the last earthquake is rapidly forgotten.

Conclusion 6: "*Countries with limited financial resources, such as Croatia, should not allow themselves to pass up opportunities. As an example, we can cite databases on structural properties of buildings (one of main problems in risk assessments) and opportunities we have missed in activities related to energy efficiency (certification), legalisation of buildings, or population census. Housing units (rather than buildings in their totality) are considered in the current population census from 2011, and also in the one planned for 2021, unlike in Albania where other data significant for risk assessment are also collected. In general, due to lack of awareness, responsible persons who manage such activities pass up the opportunities to collect indispensable data, and even to process (and implement) the existing data as sometimes we do not even know that the data are in fact available (and that they are necessary)."* – in the activities undertaken after the earthquake (damage inspections, cost estimates, determination of priorities, providing accommodation to persons who lost their homes, etc.), the lack of proper quality databases greatly complicated the organisation and functioning of the system as a whole. This does not require great investments, and it must be the first step toward better organisation of the system.

Conclusion 7: *"The Platform for Disaster Risk Reduction (under the authority of the Ministry of the Interior), within which attempts are made to link together all parties related to a particular risk, is an excellent example of good practice. The idea traces its roots to experience gained in Italy where several institutions have been constituted and linked together mainly to assess seismic risk. By unification of knowledge and centralised interconnection of experts and institutions the earthquake issues can be addressed to in a systematic and holistic manner. In the light of previous conclusions and considering the extent of necessary activities, Croatia also needs a specialized body (platform) for earthquakes which would systematically deal with the solutions to mentioned problems and work on reduction of consequences, relying on modern scientific achievements"* – taking into account the recent earthquake experience, the same conclusion can be given: establishment of an institution/centre is crucial and unavoidable for each country that seriously considers earthquake risk in its long-term strategy.

In conclusion, the Zagreb earthquake was a warning and a painful indicator not only for Croatia but also for all neighbouring countries, and even for the entire Europe. It is of crucial significance to make use of this opportunity and the increased awareness of the society, and take steps that have been proposed a long time ago in order to reduce consequences of natural disasters. The commitment of relevant persons and institutions in the Republic of Croatia should be oriented toward the strategy and vision of natural disaster risk management, with emphasis on seismic action, within an appropriate legal framework and programmes. It is important to avoid practice of establishing agencies/ funds for stricken areas after each earthquake and to avoid passing laws retroactively (after the disaster – such as in Gunja, Zagreb, etc.), but rather we should proceed step by step so as to become increasingly ready to face potential disasters (in any part of the Republic of Croatia). With this objective in mind, and based on the experience gained in other countries, we recommend establishment of an interdisciplinary centre for earthquake engineering that would gather together experts, both practicing engineers and researchers, who are committed to dealing with seismic risk management issues and who would support and advocate realisation of comprehensive and feasible measures directed toward mitigation of earthquake effects, including international networking and continuous exchanges of experience. It is also necessary to extend the existing curriculums and professional advancement programs to enable education of experts capable of efficiently dealing with these interdisciplinary issues, and Croatia should be elevated to attain the global level of research in the field of earthquake engineering. In other words, we must not allow ourselves to once again forget possible catastrophic consequences of earthquakes, but rather we must systematically prepare ourselves for peaceful coexistence with them.

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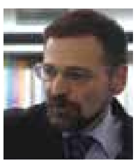

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