MARCH 22, 2020 ZAGREB, CROATIA EARTHQUAKE

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Abstract

In the early Sunday morning of March 22, 2020, amidst the COVID-19 lockdown, a M_L5.5 earthquake struck Zagreb, the capital of Republic of Croatia, and its surroundings. The epicenter was within the city, less than 10 km from the historic center and at shallow depth of 8 km. A M_L5.0 aftershock occurred 40 minutes after the main event, followed by a long-term seismic activity. These events caused a loss of one life, 26 injured and surprisingly (with regard to relatively moderate event) extensive damage to many buildings, including key infrastructural buildings, such as hospitals, schools and the Parliament. Many cultural heritage buildings of utmost importance were also damaged, e.g. the Zagreb cathedral (the largest sacral building in Croatia), which in the end lost both of its spires. About two third of all residential units in Zagreb were built before 1964, when the first seismic code was introduced in the region. The majority of buildings built later did not suffer any apparent damage during the earthquake, except some family houses in the epicentral region which were constructed or reconstructed illegally (not according to the code). However, the residential building stock comprising unreinforced masonry buildings, dating back to the 19th century and the beginning of the 20th century, sustained significant damage. Many chimneys and other unrestrained elements collapsed, many gable walls overturned, and also load-bearing walls of some buildings were severely damaged. The organization of the system for usability assessments of buildings was very challenging as it had to be initiated from scratches amidst the pandemics with no outside help. Competent precautionary measures were undertaken to preserve public safety, but heeding state regulations to limit the spread of the epidemics. This paper describes typical observed damage to buildings, as well as the context of the earthquake which, striking the capital in which almost a third of the country's GDP is generated, seriously affected the national economy and society in general. The economic losses are currently estimated at more than 10 billion euros, imposing heavy burden on authorities, but also on the local community. The conclusions drawn may be very important for the entire region and other areas with similar seismotectonic conditions and building stock.

Keywords: masonry buildings; damage; historic center; post-earthquake building inspections; COVID-19 pandemics

1. Introduction

In the early morning hours of Sunday, March 22nd, 2020, the city of Zagreb, capital of Croatia, and its surroundings were hit by two earthquakes, 40 minutes apart, with the epicenter in the northern part of the city. The local magnitude of the mainshock, registered at 06:24 a.m. local time, was 5.5 (and M_w5.4) and, according to preliminary estimates, the intensity at the epicenter amounted to VII-VIII degrees on the Mercalli-Cancani-Sieberg (MCS) scale. The magnitude of the aftershock, registered at 07:01 a.m. local time, amounted to 4.9 [1, 2].

Although the earthquakes were of moderate magnitude from the seismological aspect, they nevertheless caused a loss of one human life and huge material damage (which is currently estimated at approximately € 10 billion), especially in the protected historic center of the city, and in the epicentral area. It is assumed that approximately one fifth of the housing stock (up to 25.000 buildings) was affected by the earthquake. In the most vulnerable central part of the city, damage was inflicted on many buildings belonging to critical infrastructure, schools, hospitals and buildings crucial for proper functioning of the city and the country, as Zagreb is the administrative center of Croatia. In addition, many protected cultural monuments, sacral buildings such as the Zagreb Cathedral and numerous museums were also damaged in this seismic event (Fig. 1).

Fig. 1 – Historic center after the earthquake [3]

The earthquake generally caused moderate damage to structural systems of residential buildings, which is why the number of victims is low, and a favorable circumstance was also that the activity of local residents was reduced due 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 in normal situations. Also, there were no people in the streets, as otherwise many lives might have been lost due to collapse of numerous chimneys, parapets, gable walls, and other unsupported parts of buildings.

This paper briefly presents the earthquake impact on the Croatian capital and the organization of the field assessments of damage and usability of buildings in the aftermath of the earthquake.

2. Seismic risk in Zagreb

The city of Zagreb is located in the northwestern part of Croatia (Fig. 2), at the foot of the southern slopes of Mount Medvednica, a seismically active area, as evidenced by the devastating historical earthquake of 1880 with an estimated magnitude of 6.2. The seismic hazard of the city mainly originates from the Medvednica epicentral area, in which, according to the national seismic hazard map [4], peak ground accelerations on the bedrock of 0.2-0.28 g can be expected for the return period of 475 years. It can be assumed that most soils correspond to types B and C (along the Sava River) according to the classification of the national seismic standard [5], although seismic microzoning has not been carried out in the entire city area. Along with moderate to high seismic hazard, it should be noted that almost a third of all housing units were built before the first seismic design regulations were adopted in 1964, and an additional half of all units built after 1964 were designed for seismic loads significantly smaller than the loads according to the current

regulations [5]. In addition to the aged building stock, one should also keep in mind the often poor quality of construction, inadequate maintenance and subsequent unprofessional modifications (reconstructions).

About 20% of the population of the entire country lives in Zagreb. Moreover, the city generates about one third of the national GDP and houses most of the state administration.

Fig. 2 – Location of Croatia and the city of Zagreb

Community awareness of the earthquake risk has unfortunately been at a very low level for many years [6]. Although earthquakes have often struck the region and despite the warnings of the Croatian experts, who published the national risk assessment [7], the authorities, as well as the citizens, did not take the necessary mitigation measures. This is particularly evidenced by the Law on the treatment of illegally constructed buildings, adopted in 2012, which enabled the legalization of illegally constructed / reconstructed buildings in order to "bring order to the space". In Zagreb alone, over 100,000 requests were received. It is important to point out that the proof of mechanical resistance and stability in the legalization procedure was reduced to the statement by a certified civil engineer. As will be shown later, a large number of houses in the epicentral area were significantly damaged in the earthquake, especially those not properly designed, the ones which have undergone interventions in the structural system (reconstruction, adaptation, enlargement) and/or which were built illegally without the required building permit and safety inspections.

According to the latest official national earthquake risk assessment, for the worst possible event in the city we can expect a direct monetary loss of up to almost 16 billion EUR in housing, with widespread damage and collapses of buildings, which greatly exceeds the financial capacity of the state [7]. Furthermore, due to the extreme importance of Zagreb as the center of state administration, economy, culture, education and health of Croatia, a strong earthquake in Zagreb may have far-reaching consequences for the entire Croatian society and state stability, as shown by this March 22nd earthquake of only moderate magnitude.

3. The March 22nd, 2020 earthquake

Basic data about the event are given in the Introduction, while a more detailed information can be found on the website of the Seismological Survey [2] and in [1, 8, 9].

At the time of the event, only two seismic stations and four additional strong-motion stations were operational in the 20 km circle around the epicenter. The elastic response spectra of the horizontal components of the mainshock recorded at the strong-motion station, located 1.75 km away from the main town square, are presented in Fig. 3, in relation to the code elastic spectra (labelled as *EC8*) for different return periods (95, 225 and 475) and type C soil according to the valid seismic standard [5]. The peak ground acceleration recorded at that station during the main shock was 0.22 g for the north-south component (N-S) and 0.18 g for the east-west (E-W) component. The preliminary results [10] show that the PGA amplification due to local soil conditions, measured at two strong-motion stations, is probably less than 20%.

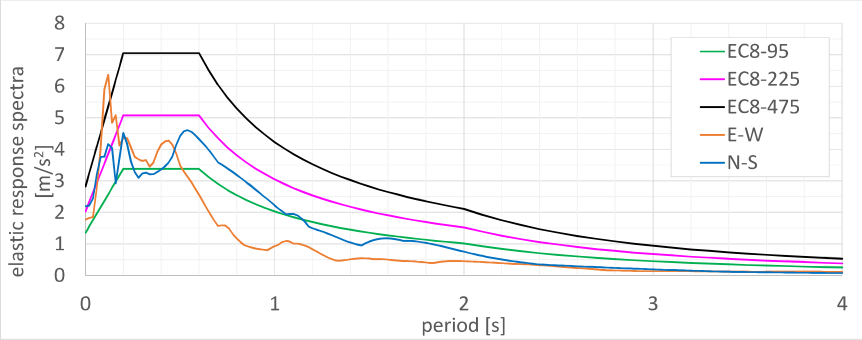

Fig. 3 – Elastic response spectra of the recorded motions and code elastic response spectra

After the March 22nd event, the seismic activity was intensified, and in total, more than 1,400 earthquakes were recorded in the next forty-five days [8]. Epicenters of these aftershocks which occurred until June 1st, 2020 are presented in Fig. 4.

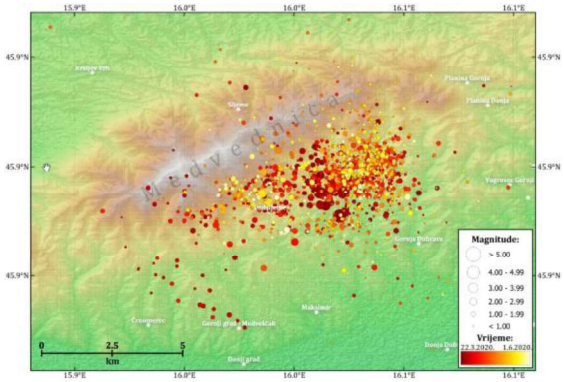

Fig. 4 – Preliminary locations of seismic epicenters, 22nd March 2020 to 1st June 2020 [1, 9]

4. Organization of the field assessments of damage and usability of buildings

A brief overview of the system for post-earthquake assessments of damage and usability of buildings, that was a part of the disaster response system, will be presented in this chapter.

It is important to point out that the earthquake struck during the COVID-19 crisis, which already strained the system, and after the earthquake this crisis significantly limited the organization of the field damage inspections. Initially, it was crucial to equip all volunteers with protective equipment, and then to adequately educate them about procedures for conducting assessments, with the advice of epidemiologists being crucial. Furthermore, due to the temporary ban on movement out of the place of residence, it was not possible to activate the help of experts from other cities or international assistance. Fortunately, a large number of volunteers-engineers responded to the call for assessments, so that numerous shortcomings of the preparatory phase of the system, especially in the organization and capacities, were mostly overcome.

Perhaps the biggest problem was that before the earthquake, there were no official forms for inspections of buildings, nor was there a systematic training of experts who could participate in the post-earthquake inspections of buildings. There had existed only individual initiatives which in the end turned to be the most important in setting up the organization of the field assessments. For example, immediately after the earthquake, in parallel with the activation of civil protection services, the meeting between the Emergency Management Office of the City of Zagreb, the Directorate of Civil Protection of the Ministry of Interior and the Faculty of Civil Engineering (prof. Atalic and prof. Uros) was held and a crisis headquarters for the operational management of building damage assessments in the field was established. At that time, the scale of the disaster was unknown, and it was decided to set up the headquarters in he Emergency

Management Office. The organization of the system was improvised from scratch, applying the knowledge gained in European projects and numerous exercises with civil protection teams, adapted to the actual situation on the ground. The first hours and days were very demanding for the organization of the system due to the lack of prior preparation and training, but with the help of numerous volunteers, institutions and people within the city and state services, the system improved by the day. Finally, all experts were equipped very quickly, assessment forms were prepared, training for conducting assessments was prepared and provided, all critical infrastructure buildings were inspected (e.g. hospitals), a system for receiving citizens' applications was organized (telephone, e-mail, internet application, etc.), an application for field assessments that worked on smartphones was programmed, WhatsApp groups for consulting and coordination of assessments were created and a GIS-based system was established. The use of the GIS-based platform (Fig. 5-6) was crucial in view of the COVID-19 crisis, as it enabled direct monitoring of field assessments results and presentation of the results to all relevant institutions without unnecessary contacts (the platform also contained data on isolated and self-isolated persons).

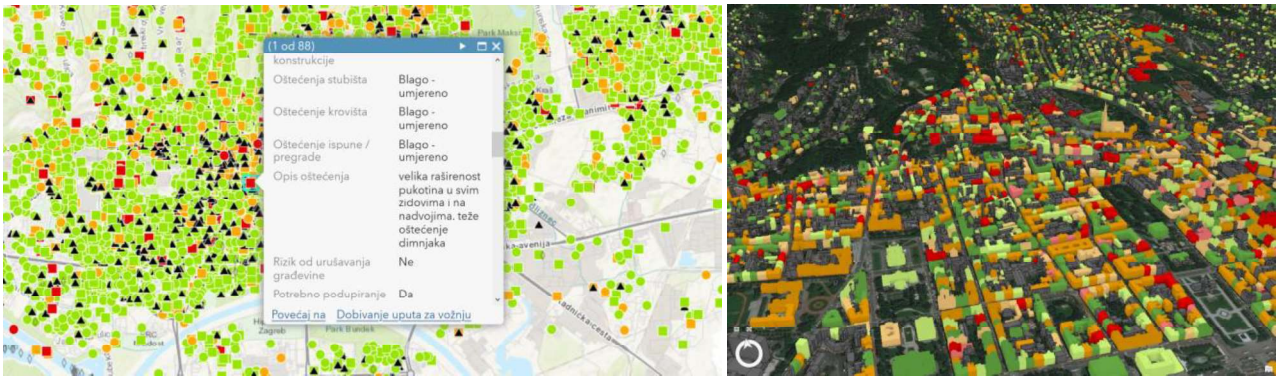

Fig. 5 – GIS-based Building Usability Database with example data from field assessments (in Croatian) [3] and the perspective view of the historical center according to buildings usability tags

In addition to assessments of damage and usability, the city and state headquarters organized the clearing and removal of potentially hazardous parts of buildings led by the Public Fire Brigade of the City of Zagreb, which was joined by volunteer alpinists. For example, according to the official report of the City Office for Strategic Planning and Development of the City from June 30th, 2020, it was necessary to remove the chimneys on 5,166 buildings. The Croatian Red Cross provided accommodation, food and care for people whose homes were unusable, and a tent settlement was erected. Numerous activities were performed simultaneously, and were organized by the city and state headquarters formed after the earthquake.

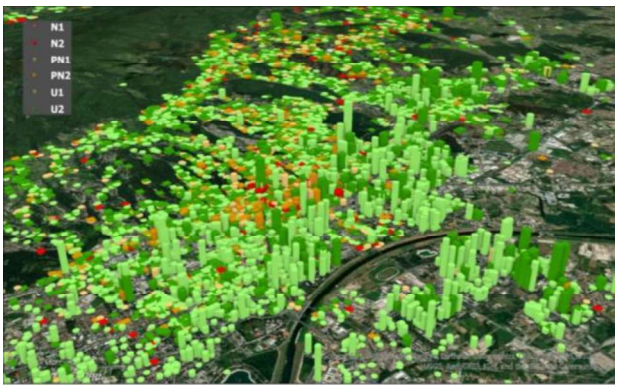

Fig. 6 – Damage to residential and commercial-residential buildings according to usability tags (colors) and gross floor area of buildings (height of columns) on a perspective view of the city of Zagreb [8]

In the first days, the focus was on assessing the usability of buildings, because urgent measures to mitigate the risk of collapse of buildings parts to adjacent buildings and/or driveways had to be implemented,

as soon as possible. Moreover, it was necessary to temporarily take care of the people and to gain preliminary insight into the extent of damage. During the field assessments, usability tags were given to buildings 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). It is important to point out that cultural heritage buildings were additionally inspected in detail, according to special forms by the Ministry of Culture.

In total, over 42,000 applications for inspections of buildings were received from citizens, many of which related to the same buildings as citizens often reported their dwellings separately, and some buildings had to be inspected several times (for example, after removing a particular hazard). Finally, about three months after the earthquake, the inspections were officially stopped. In total, more than 25,000 inspections were performed, with about 75% of buildings receiving green tag, about 20% yellow tag and about 5% red tag (Fig. 7). The usability database is still the only database that covers most of the issues of post-earthquake damage, so that various decisions of institutions were based on its data (co-financing of costs for chimneys / roofs, organization of replacement accommodation, distribution of rehabilitation materials, bank loans, preliminary damage assessment and reconstruction costs as basis for the adoption of the Law on Reconstruction of Earthquake Damaged Buildings, assistance from international funds, etc.). It is important to point out that the initial idea of database was to increase the safety of citizens, so that the application of such a database outside this framework may be dangerous, especially in decisions related to the allocation of significant financial resources.

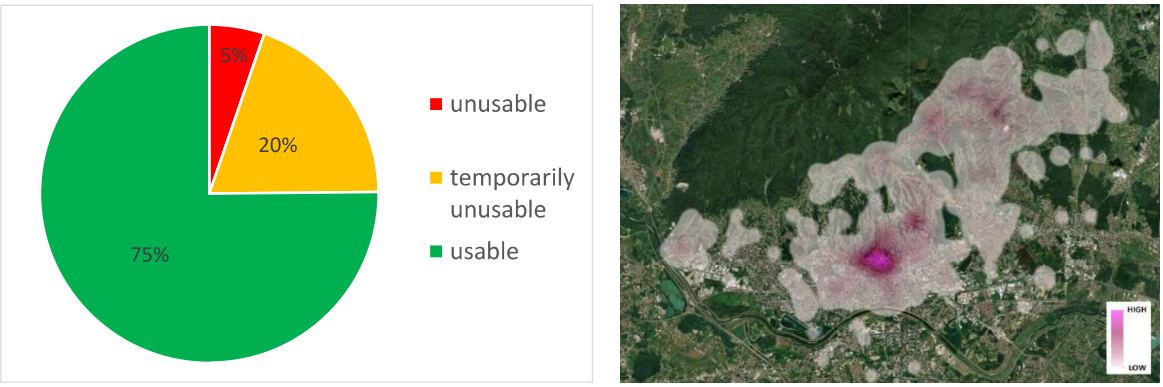

Fig. 7 – Usability of buildings in the city of Zagreb - 25,528 processed applications on June 30th, 2020 (left) and heatmap of unusable buildings (N1 and N2) (right)

5. Earthquake impacts

From the seismological point of view, the earthquake was of moderate magnitude, but it nevertheless caused the loss of one life and a widespread material damage (current estimates of reconstruction costs are around EUR 10 billion). The low number of human casualties is primarily attributed to predominantly minor to moderate damage to structural systems of residential buildings. A further mitigating factor was a reduced activity of residents due to the imposed restrictions related to the COVID-19 pandemic. Unfortunately, some public buildings such as hospitals, schools and kindergartens have been severely damaged. For example, almost 200 buildings in the sector of health care were affected by the earthquake of which moderate to heavy damage was recorded in 39 buildings and heavy in 8 buildings. It is important to point out that usability assessment of hospitals was a very difficult task for engineers, because depending on their decision it had to be decided whether the patients would be removed from the equipment that provided them with life-essential medical care. The question that arose was where people, injured in higher-intensity earthquake, would be received and treated. If we consider that more than 60% of all hospitals in the city are unreinforced masonry buildings constructed before the first seismic standards had been adopted and that they were not seismically

retrofitted later, it should be clear that the situation is worrying. Furthermore, the situation with education buildings is similar. In the education sector, more than 500 buildings were damaged in the earthquake, of which almost 40 % are schools. Fortunately, the earthquake occurred while those facilities were empty. However, the question of safety of children in the event of an earthquake recurrence arises. (Low) awareness and understanding of the earthquake risk could have also been noticed in months after the earthquake, when citizens and state institutions took urgent measures in which the level of safety of buildings was not increased (but only the most necessary repairs being made).

As already mentioned in the Introduction, the earthquake also affected invaluable cultural heritage (Fig. 8), such as the largest Croatian sacral building, the Zagreb Cathedral. The stone spire of its southern bell tower collapsed and caused damage to the roof of the cathedral. During the inspection, significant damage was observed to the spire of northern bell tower as well, which had to be urgently removed. In addition, the balustrade above the apse was destroyed, and the façade walls and vaults were significantly damaged. The Basilica of the Sacred Heart of Jesus had almost a third of its ceiling collapsed. Numerous other churches, museums and other buildings, individually protected as cultural heritage buildings, were also damaged (almost 500 such buildings). In addition to structural damage, the earthquake also affected numerous decorative elements on the buildings that give the city its identity, so that restoration will be demanding also from the point of view of the conservators.

Fig. 8 – Damage to cultural heritage: the Zagreb Cathedral, Mirogoj cemetery, Basilica of the Sacred Heart of Jesus, Croatian restoration institute and Croatian Academy of Sciences and Arts

Nevertheless, the most affected by the earthquake was the housing sector, which accounted for almost two-thirds of the total damage, according to [11]. Unreinforced masonry buildings with timber floor systems were damaged the most (very often out-of-plane mechanisms occurred– Fig. 9), but other structural types were also affected (for example, reinforced concrete frames with infills or in general, buildings that do not comply with the modern seismic standards). Older masonry buildings were not designed for horizontal loads, and unfortunately often poorly maintained, so that material deterioration is pronounced (especially in buildings that do not have a façade).

Fig. 9 – Out-of-plane mechanisms frequently observed in the buildings damaged by the Zagreb earthquake [12]

In the historic center, the traditional masonry buildings were built in relatively large building blocks. The sidewalls of these buildings are adjacent to each other and, although there are no common gable walls,

they often lean against each other without any partition. Due to frequent protrusions for drains and/or used water piping, windows, or due to various interventions over time, gable walls of adjacent buildings are often wedged or joined together. It can therefore be assumed that buildings that are not located at the corner of the block behave more or less as interconnected. The width of the building determines the spanning direction of the floor joists. In general, the floor slabs are supported by the longitudinal walls parallel to the street. This is the stronger load-bearing direction for lateral seismic forces, whereas in the perpendicular weaker direction the stairwell, separation and/or gable walls are unsuited to support significant loads.

The concept of 'block of buildings' appeared to be less vulnerable to earthquake according to observed damage during inspections. The structural characteristics of the adjacent buildings contact, however, remain uncertain and there is a complex interaction in the dynamic response. This further complicated the identification of the cause of damage. Buildings at the block corners are generally built with load-bearing walls in both directions, a system which provided relatively high seismic resistance. Problems were noticed in buildings that exceed the height of the rest of the buildings, a common construction practice in Zagreb. There, the damage was concentrated to the prominent "free" floors. Buildings without a neighbor on one side were also susceptible to earthquake damage. Such was the case when the building row was interrupted due to demolition of dilapidated buildings thereby freeing-up space for car parking and access. Damage to these buildings was mainly observed on the free side walls, and occasionally in certain walls within the floor plan and walls facing the neighbor.

Fig. 10 – Collapse of chimneys and top part of the gable walls, damage to roof structures and to parapet walls [3, 13]

In brief, typical observed damage includes collapse and damage of chimneys, attic gable walls and various other unsupported elements (attics, domes, etc.) (Fig. 10), separation of gable walls along the height (Fig. 11), roof damage, in-plane damage of masonry walls with characteristic diagonal cracks, often along mortar bed joints (Fig. 12), damage to lintels (Fig. 13) and vaults, staircases and partition walls. They are described in detail in [8], but few examples are shown in the following Figures.

Fig. 11 – Separation of walls along the height due to out-of-plane mechanisms [3, 14]

Fig. 12 – Diagonal cracks in walls [3, 14]

Fig. 13 – Damage to lintels [3]

Furthermore, decorative elements such as roof domes, portals, cornices on facades, and decorative sculptures, have also suffered considerable damage (Fig. 14). Usually, these elements were not properly restrained. There are still many elements that have not been removed or properly retrofitted, so that despite their cultural value, they represent considerable hazard in the case of a new earthquake.

Fig. 14 – Damage to decorative elements

As for the epicentral area, it should be noted that damage was very frequently observed in masonry houses with poor quality of construction and where structural systems were further weakened by additions and renovations. Very often, addition of one or more floors was subsequently made without strengthening the ground floor, although in new floors one may find walls with tie beams (not extended to the ground floor). On top of that, board-based floor with rubble was often removed during renovation and replaced with concrete slab without reinforcement, and without adequate anchoring into walls. Fig. 15 highlights several characteristic examples from the epicentral area.

Fig. 15 – Damage to houses in the epicentral area [3, 8]

6. Reconstruction process

Shortly after the earthquake, the drafting of the Law on Reconstruction of Earthquake-Damaged Buildings was initiated, but the Law was not in the end passed until September 2020. The law is intended primarily to help affected communities recover faster. It regulates organizational and financial procedures for reconstruction of damaged buildings, possible demolition and construction of new family houses.

As engineers had to initiate detailed inspections of buildings and retrofit designs as soon as possible, the expert guidelines for reconstruction, which were supposed to be part of the Law, were published at the end of June 2020 as amendments to the Technical Regulation for Structures. Reconstruction methods and guidelines are specified depending on the building occupancy and the degree of damage. They prevent that damaged buildings are restored by maintaining the same details that performed poorly during this moderate magnitude earthquake. Instead, interventions are proposed that improve the dynamic behavior of buildings without high economic costs and relocation of occupants (build back better principle). Residents will be made aware that the strength of the damaged buildings was low even before the earthquake and that it is practically impossible to attain the resilience required by current standards. A high safety level can only be guaranteed by implementation of complex and expensive interventions, which for most of the housing stock is not economically viable and/or technically feasible. These guidelines attempt to solve the problem optimally, considering the previously stated and acknowledging technical correctness and economic cost-effectiveness of reconstruction measures implementation. Each building shall receive a seismic certificate in relation to the level of renovation and proven mechanical resistance and seismic stability. It is expected that these measures will additionally raise awareness of those responsible for safety of their properties and will motivate them to act accordingly in the long run.

Although the legislative framework for reconstruction was adopted, at the time of writing this paper (almost a year after the earthquake) it can be stated that systematic reconstruction of the city has not yet begun (except for individual initiatives) and that it is still dangerous to walk around the historic city center (especially after M_w6.4 Petrinja earthquake that occurred in December 2020 at a distance of approximately 50 km).

7. Conclusions

Although experts have been warning about the high earthquake risk in the city of Zagreb for many years, the earthquake that hit Zagreb on March 22nd, 2020, caught both citizens and the system completely unprepared. It exposed the lack of activities and strategies aimed at mitigation of seismic risk, as well as the long-term neglection of the building stock. Although the tremor was significantly less severe (only M_L5.5) than expected at the location (M6.3-6.5), it caused one casualty, 26 injuries and widespread damage. The most affected were the unreinforced masonry buildings in the historic city center and in the epicentral area, and many buildings of critical infrastructure and cultural heritage buildings were severely damaged. The current estimates of the total economic loss are in the range of 10B euros mainly for the expected reconstruction costs. It is expected that the recovery process will take many years.

The system for assessments of damage and usability of buildings was improvised after the earthquake and it can be stated that despite the shortcomings of the preparation phase it worked relatively well, primarily thanks to the sacrifice of many individuals who compensated for the shortcomings of the official disaster response system.

Nevertheless, we hope that this earthquake of only moderate magnitude was a great warning to everyone in Croatia, but also in the region, that will be taken seriously and that will encourage additional efforts to improve our community's resilience to disasters.

8. Acknowledgements

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9. Copyrights

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