Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-50405
www.engineeringscience.rs

iipp publishing

Journal of Applied Engineering Science
Vol. 22, No. 2, 2024
Professional Paper
Paper number: 22(2024)2, 1183, 239-244

IMPACT OF DEVASTATING EARTHQUAKES IN CROATIA IN 2020

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At the beginning of 2020, the area of Zagreb was hit by an earthquake of magnitude Mw5.4, where a significant number of buildings in the historic core of the city was damaged. Not long after that, at the end of the same year, a strong earthquake of magnitude Mw6.4 hit the area of Sisak-Moslavina County, which is about 50 km away from Zagreb. It was a significantly stronger earthquake that had enormous consequences for that region and much wider. Earthquakes struck during the Covid-19 pandemic and shocked the whole country. This multi-hazard scenario surprised everybody, as the country was not ready. Regardless, in the first hours after the earthquake, a system of damage assessment was established based on experts from the academic and professional community, which would later grow into Croatian Centre for Earthquake Engineering. From a technical point of view, this paper refers to the response of the system to the earthquakes, post-earthquake activities of Croatian Centre for Earthquake Engineering and with challenges and problems in organization of damage inspection of the buildings. The paper briefly describes the earthquake scenarios in Zagreb and Petrinja. The typical vulnerable buildings typology and damage are described, trying to find explanations and guidelines for the future earthquakes. The focus is on the unreinforced masonry buildings and out of plane failures which prevail in damage, especially in historical buildings of cultural heritage. Such significant damage to buildings of historical importance makes us think about the way of their future protection and restoration that will follow. Also, some positive experiences in construction practice are highlighted. At the end, a perspective is given for the further development and improvement of the post-earthquake response system, and the need for cooperation of several professions is highlighted in order to obtain a synchronized response to earthquakes. In addition, international cooperation in the organization of the system before and after the earthquake is of key importance.

Keywords: earthquakes in Croatia 2020, impacts of earthquake, post-earthquake damage assessment

1 INTRODUCTION

Southeast Europe is a seismically active region. According to Seismic hazard map for Croatia [1], PGA is up to 0.38g on the bedrock for 475 years return period [Figure 1]. With considerable seismic hazard, the significant seismic risk is affected by both the vulnerable typology and high exposure. Additional problem is that the information on building inventory is very limited and in addition, the building stock is relatively old (>22% buildings built before 1964 and additional 41 % before 1981). The European Seismic Risk Model [2,3] concludes that the earthquake risk is very high and can have potentially catastrophic consequences and is unacceptable in relation to the country's capacities. Although there were teams at the faculties that work on a seismic risk assessment of Republic of Croatia [4], at the national level this threat was not recognized. However, during the 2020 two earthquakes hit Croatia and shocked the whole country. Additionally, it was the Covid-19 pandemic and the country was not ready for this multi-hazard scenario. The earthquake caused enormous damage to the building stock, especially in the historic centres of Zagreb, Petrinja, Sisak and Glina.

Immediately after the earthquake, a system for post-earthquake assessment was established based on experts from the Faculty of Civil Engineering in Zagreb and the Croatian Chamber of Civil Engineers, with support from the Emergency Management Office of Zagreb and Directorate of Civil Protection. This team organized all post-earthquake activities related to evaluating damage and the usability of structures [5,6]. Very soon, the entire civil engineering community responded and they joined together to help. Scientists, professionals, and emergency responders started to collaborate. The objective was to help people whose homes have been damaged. This team will become a Croatian Centre for Earthquake Engineering (CCEE) and will be the basis for future earthquake mitigation activities in Croatia. This paper will present the most important conclusions after a series of earthquakes that hit Croatia in 2020 and a brief overview of the activity of CCEE will be given.

2 ZAGREB EARTHQUAKE

Zagreb is administrative, cultural, scientific and economic center of Croatia with 20% of all population of Croatia and approximately 1/3 of the country's GDP according to Croatian Bureau of Statistics. Zagreb is home to the central government, administrative authorities and almost all ministries, as well as the largest Croatian companies, media, many scientific and cultural institutions, hospitals, industrial plants and historical monuments. According to Seismic hazard map [1] PGA goes up to 0.28g for 475 years return period. On Sunday, March 22, 2020, the city of Zagreb was shaken by two earthquakes, with the epicenter located in the northeastern part of the city. The local magnitude of the main earthquake was Mw 5.4, while the aftershock had a magnitude of Mw 4.9 [7]. In one aftershock sequence, more than 1000 earthquakes were recorded within the next month. The elastic response spectra of the horizontal

components of the main earthquake recorded at the strong-motion station [7], located 1.75 km from the city center [7] are shown in Figure 4. The figure also shows the elastic Eurocode spectra for different return periods (95, 225 and 475) and soil type C, which corresponds to 5% damped pseudo-accelerations. The peak ground acceleration recorded at this station during the main earthquake was 0.22 g for the north-south (N-S) component and 0.18 g for the east-west (E-W) component. The strong motion spectra show higher amplitudes in the short-period range (<0.5 s), which is very unfavorable for masonry buildings.

The earthquakes caused a loss of one life, injured 26 people and caused enormous damage to property, particularly in the epicentral area. A fifth of the housing stock (up to 25,000 buildings) was affected by the earthquake. Schools, hospitals and buildings that are important for the functioning of the city and the country were severely damaged. Many protected cultural monuments, sacral buildings and numerous museums were damaged (Figure 2). Due to the earthquake about 30,000 people left their homes and 5,816 buildings were unusable. The total damage cost was 11.3 billion EUR and the prediction of reconstruction cost was more than 17.5 billion EUR [8].

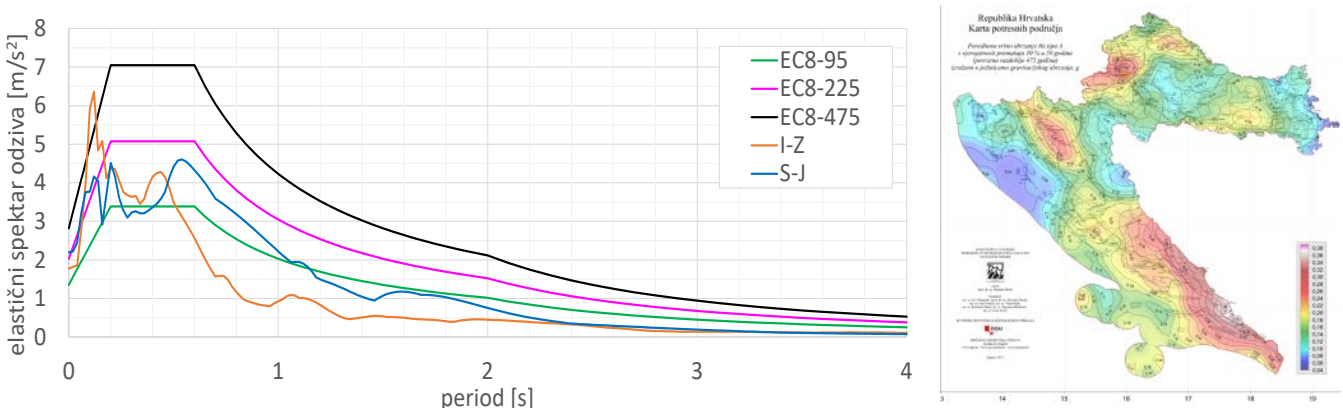

Fig. 1. (a) The elastic response spectra of Zagreb earthquake (station near city centre) source: Croatian Seismological Survey, Department of Geophysics, Faculty of Science, University of Zagreb, (b) Seismic hazard map of Croatia for 475 return period [1]

Due to the Covid-19 pandemic, gatherings were banned, which was particularly important for centuries-old churches that were severely damaged. In addition, due to the pandemic and in the early morning, there were no people on the streets, as otherwise numerous chimneys, parapets, gable walls, bricks and other unsupported parts of buildings which collapsed could cause serious injury.

Traditional masonry buildings in Zagreb were mostly built as systems of load-bearing walls and wooden floor structures with inadequate connections. Generally, the floor structures are supported by the longitudinal walls running parallel to the street [9]. The buildings in the historic city centre are mainly built in relatively regular and large blocks with a complex interaction (Figure 2). Due to lack of maintenance, the material deteriorates quite quickly, increasing the inhomogeneity of the walls and the loss of binding material. Cantilevered high walls and their out-of-plane mechanism are the biggest problem (Figure 2).

Typically observed damage includes collapses and damage to chimneys, gable walls and various other cantilevered elements (attics, cupolas, etc.), detachment of gable walls at height, roof damage, in-plane damage of masonry walls with characteristic diagonal cracks - often along mortar bed joints, damage to lintels and vaults, stairs and partitions [9,10]. In addition, decorative elements were significantly damaged, which, despite their cultural value, pose a great danger in the event of another earthquake (Figure 2). The classification and degree of damage as well as the usability of the buildings after the earthquake are described in detail in [11].

Fig. 2. Zagreb earthquake (source: HCPI, 2020; AIR-RMLD d.o.o.)

The earthquake inflicted enormous damage to buildings belonging to the protected architectural heritage. Almost 500 historical buildings were partially damaged and more than 10% of them were partially destroyed (Figure 2). The big problem were health care facilities as the most important infrastructure in the post-earthquake response and recovery. Many of them showed severe structural damage and several major hospitals had to evacuate patients and

medical staff immediately. Most of them date from the late 19th to early 20th century and were built before 1960 using unreinforced masonry.

The damaged residential buildings in the epicentral area were built mainly after WW2. They are mainly unreinforced masonry structures or mixed systems without any standard (Figure 3). The lightweight roofing material is generally attached to the upper edge of the walls or tied loosely. The floor slabs consist mainly of prefabricated elements or reinforced concrete slabs. Mostly of them in epicentral area have significant in-plane damage and diagonal cracks. The typical damage is shown in Figure 3.

Fig. 3. Zagreb earthquake [14]

3 PETRINJA EARTHQUAKE

On December 29, 2020, a strong earthquake of magnitude M_w 6.4 struck the central Croatia near Petrinja and Glina with epicentre 4.5 km southwest of Petrinja which is about 50 km SE from the Zagreb. The earthquake was at depth of 6-7 km [12]. A day before, foreshock of magnitude M_w4.9 hit the same area and caused a panic in the community. Also, this foreshock probably reduced the number of casualties because many residents left their damaged houses. According to USGS and PMF prediction, the PGA on bedrock at the epicentre was 0.3*g* and with soil amplification, up to 0.5*g*. Tragically, the event caused seven deaths, 15 of injuries and about 15,000 people who had to be temporarily housed. In total, approximately 4,000 families lost their homes.

More than 50,000 building inspections have been conducted by engineers. The older unreinforced masonry buildings were most damaged. Many of these old buildings are in the historic centers of Petrinja, Glina, and Sisak, which are protected cultural heritage sites (Figure 4.)

Fig. 4. Petrinja earthquake, (a) center of Petrinja [14], (b) Church of St. Nikola and Vid, Žažina (source: Ministry of Culture and Media) (c) Church Mother of God, Gora [14]

An initial assessment in February 2021 estimated economic losses at 4.8 billion EUR, while the projections on recovery and reconstruction needs were at 8.4 billion EUR [13]. The local population suffered serious psychological trauma. Also, Zagreb suffered a significant progressive damage from the Petrinja earthquake.

Significant destruction has been documented for churches and chapels. Extensive structural damage was evident in the bell towers of churches. The absence of connecting anchors between the tower walls resulted in significant structural damage, leading to potential collapses due to the numerous aftershocks. Infrastructure such as bridges, roads, drainage systems and utilities were also damaged, and various soil failures such as landslides, sinkholes, and soil liquefaction occurred. In many areas the ground soil is not safe for reconstruction or building of new houses.

Majority of the brick and lime mortar masonry structures with wooden floor structures in historical urban centres dates to the late 18th and early 19th centuries. The roof structure consists of timber beams, often lacking adequate stabilizing components. The usual damage was the out-of-plane failure of the walls. The ground floor's load-bearing walls sustained minimal damage, unlike the upper floors. There was extensive damage to spandrels and arches, and slight to moderate in-plane damage of primary walls (Figure 5). Consequently, the failures of gable walls and facade walls on the upper floors led to destabilization and, in many cases, the collapse of the roof structures.

Fig. 5. Petrinja – typical damages [14]

In many buildings with relatively stiff floor structures, in-plane failure mechanism was observed (Figure 6). The shear mechanism in these walls typically showed diagonal cracks and joint cracking due to the substandard mortar quality.

Fig. 6. Petrinja [14]

Newer family houses are usually built of confined masonry with semi-precast floor structures. This type of buildings started becoming prevalent mainly after 1995., particularly during the post-war reconstruction period. This typology withstood the earthquake quite well and the prevalent form of damage was cracks in plaster and the slight shear cracks in masonry infill walls, primarily due to stiffness and deformation mismatch between the walls and reinforced concrete frames. In contrast to the other categories of structures, reinforced concrete buildings exhibited notably lesser damage. However, the lack of transverse reinforcement has proved fatal for some reinforced concrete buildings.

4 REACTION AND EMERGENCY RESPONSE

In Croatia, there were experiences from the previous earthquakes and risk assessments, but there was no organized system in the country to carry on the post-earthquake assessment. On the Faculty of Civil Engineering at University of Zagreb, numerous activities were carried out to increase the community's earthquake preparedness. There were many initiatives and knowledge gained through exercises and training for post-earthquake inspection of buildings and field missions with Civil protection teams, but it needed to be raised to a higher level.

Immediately after the earthquake, post-earthquake building evaluation of buildings started in collaboration of Faculty of Civil Engineering in Zagreb and the Croatian Chamber of Civil Engineers, with support from the Emergency Management Office of Zagreb and Directorate of Civil Protection. Because of COVID 19, there was no help for on-site assessments from abroad. In the first days after the earthquake, the Croatian Centre for Earthquake Engineering (CCEE) was established, which will later lead most of the activities after the earthquake in Zagreb and Petrinja.

Fig. 7. a) Mobile application (Collector for ArcGIS) b) Sisak - buildings usability c) headquarter of CCEE in Petrinja [14]

The training of volunteer engineers was organized. There was no official form for post-earthquake damage assessment of buildings, but only the unofficial form which was similar to Italian AEDES [15], adapted to the local building stock. In the first days, a mobile application (Collector for ArcGIS) was developed in cooperation with the

company GDI, which enabled real-time monitoring of inspections in the field (Figure 7). This approach proved crucial, particularly in the initial phases, as it guided daily decision-making for priorities such as emergency interventions, road rehabilitation, shelter arrangements, and more, all of which were determined based on the digital database. After the experience of the Zagreb earthquake, the building inspection methodology and decision-making system rose to a higher level. More than 1,700 engineers from all over Croatia participated in the process of usability assessments in Petrinja.

Apart from building damage assessment, CCEE had numerous other activities during the emergencies like securing the unstable buildings and conducting assessments on essential facilities and critical infrastructure. Different teams often worked together in an interdisciplinary manner. Civil engineers and firefighters cooperated in operations of removing dangerous and hanging parts of buildings. Together with the Croatian Red Cross, the Civil Protection Headquarters organized the transport of mobile homes and containers and coordinated the arrival of humanitarian aid. The Croatian Mountain Rescue Service carried out work at height, such as removing chimneys and securing damaged gable walls, and took part in the transportation of mobile homes and containers. The police took care of civil security and traffic control, which had come to a standstill in the first few days due to the many damaged roads and debris on the streets.

After the post-earthquake activities subsided, CCEE actively participated in various post-earthquake initiatives such as publication of retrofitting manuals, establishment of interdisciplinary workgroups for reconstruction, advising local and state entities on reconstruction matters, collaborating with the World Bank experts on damage assessment and reconstruction cost estimation and engaging with the local and national institutions on earthquake risk before a new earthquake strikes.

Furthermore, the association CCEE Intervention Service was established to create an official organizational unit capable of responding effectively to major disasters across all regions of Croatia. It was founded by 40 stakeholders, including 16 legal entities such as faculties, chambers, and professional associations, as well as 24 individuals, notable volunteers with significant experience in disaster response, especially during earthquakes. Given their important role within the civil protection system, the heads of CCEE-IS actively participate in the Civil Protection Headquarters' operations during both emergencies.

5 CONCLUSION

Strong earthquakes occurred in Croatia in 2020, which caught us unprepared. Although there were initiatives by scientists and experts to raise the preparedness before the earthquake, it was necessary to learn it the hard way.

In addition to numerous problems that emerged during the damage assessment process, related to the lack of systematic databases on buildings, a system was efficient and quick with some improvisations which gave extremely good results. Lessons learned after the Zagreb earthquake were critical to emergency response in Petrinja area. The positive was that the academic and engineering community became very engaged and the level of knowledge was raised (the process is still ongoing). Citizens are more aware of seismic risk and this should be used to implement some additional necessary steps.

The earthquakes that occurred also revealed deficiencies in the maintenance system of old and valuable historical buildings which are usually unreinforced masonry buildings with flexible floors which are not connected to the walls well. It is necessary to change something in the way of their reconstruction and maintenance.

The earthquakes that struck Croatia in 2020 served as a stark warning to decision-makers in the country, shedding light not only on Croatia's vulnerability but also on neighbouring countries. This moment is crucial, presenting an opportunity to capitalize on heightened societal awareness and implement long-proposed measures to mitigate potential disasters.

The establishment of the Croatian Centre for Earthquake Engineering (CCEE) is a significant step forward. CCEE serves as a hub for experts, encompassing both practicing engineers and researchers, who are dedicated to addressing seismic risk management challenges.

6 ACKNOWLEDGEMENT

The authors extend their appreciation to many colleagues and volunteers who conducted inspections of buildings and many other post-earthquake activities.

The financial support from the Croatian Science Foundation (grant number UIP-2020-02-1128) is gratefully acknowledged.

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Paper submitted: 10.03.2024.

Paper accepted: 11.06.2024.