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CASE STUDY REPORTS

The December 2020 magnitude (*Mw*) 6.4 Petrinja earthquake, Croatia: seismological aspects, emergency response and impacts

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Abstract

On December 29, 2020, nine months after the March *Mw* 5.4 Zagreb earthquake and amidst the COVID-19 lockdown, a devastating *Mw* 6.4 earthquake struck near the town of Petrinja, about 50 km SE from the country's capital Zagreb. It was preceded by the *Mw* 4.9 foreshock from the day before. The main shock claimed 7 fatalities and caused widespread damage. Historical centers of nearby cities with invaluable heritage buildings were significantly affected as were the many residential buildings, built mainly of unreinforced masonry. Damage was observed as far as 60 km from the epicenter. This paper summarizes the seismological aspects of the *Mw* 6.4 Petrinja earthquake, the emergency response and the main impacts to people and buildings. The description and findings are based on the field observations and a series of post-earthquake activities led by the team of the Faculty of Civil Engineering, University of Zagreb. Typical damage to buildings and usability data are presented with examples based on 50,000 inspection results. By far the most affected were the unreinforced masonry buildings, followed by confined masonry, whereas reinforced concrete buildings were the least affected. The total direct and indirect losses are estimated to 4.8 billion EUR. The provided information represents a useful basis and impetus for improving emergency action and long-term disaster reduction plans in other regions with similar building exposure and seismotectonic settings.

Keywords Physical damage · Masonry buildings · Emergency response · Post-earthquake survey · Social impacts

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1 Introduction

On December 29, 2020, at 12:19 p.m. CET, a devastating *Mw* 6.4 earthquake struck the larger area of the town of Petrinja in central Croatia, about 50 km SE of the capital Zagreb. That was the strongest earthquake that occurred in Croatia in the recent history. The epicenter of the earthquake was just 6 km southwest of Petrinja. Extensive damage to buildings was widespread and streets were full of debris in Petrinja, the nearby towns of Glina and Sisak, as well as throughout the Sisak-Moslavina County and neighboring counties, including some minor damage in Zagreb. The loss of life of 7 individuals, dozens of injured people requiring medical care and about 15,000 temporarily accommodated people are the most tragic consequence of this unfortunate event.

The main shock was preceded by a foreshock with *Mw* 4.9, that hit approximately the same area the previous day at 6:28 a.m. CET. Because of this, a number of the damaged buildings were abandoned, which likely contributed to fewer casualties from the main event. The foreshock also alerted the civil protection authorities, some of which were already onsite to assess losses when the main shock occurred. Thus, the civil protection system was readily involved in the emergency response, including police, fire brigades, civil protection intervention units, the Croatian Red Cross, the Croatian mountain rescue service, the army and numerous volunteers. A number of engineering experts joined the damage assessment teams as part of the Croatian Center for Earthquake Engineering (CCEE), the national seismic disaster reduction and preparedness platform established following the March 2020 *Mw* 5.4 Zagreb earthquake.

The first days after the earthquake were particularly critical since many homeowners did not want to leave damaged houses invoking various reasons, e.g., taking care of the livestock, fear of robbery, etc. Temporary accommodation containers were dispatched to shelter affected families in the area, but not quickly enough to meet all the immediate needs. The situation was aggravated by the winter conditions, the ongoing COVID-19 pandemic and particularly as part of the population at risk, e.g., elderly population, was scattered in remote rural villages difficult to access.

A total of 50,000 building inspections were carried out as of March, 2022. Most of the damage was sustained by older unreinforced masonry buildings built before the adoption of the first official seismic regulations implemented in 1964 following the devastating 1963 Skopje earthquake. In these regulations, the lateral force coefficient was calculated as the product of three factors: seismic coefficient depending on the seismic intensity, soil type and building type/use; dynamic coefficient for the ith mode shape, and the coefficient for the ith mode shape and the kth position in the height of the building. According to the hazard map valid at that time, defined considering the maximum observed intensities according to the MCS scale, most of Sisak-Moslavina County was in the seismic zones VII (e.g. Glina) and VIII (e.g. Petrinja and Sisak). For the medium soil, the lateral force coefficient was between 0.0375 for the zone VII and 0.075 for the zone VIII (assuming dynamic coefficient of 1.5 and 1.0 for the coefficient depending on the mode shapes). A very interesting paper on the development of the seismic codes in the former SFRY can be found in Milutinovic et al. (2022).

Many of those aging buildings make part of the historical centers in Petrinja, Glina and Sisak, with many of them protected as cultural heritage. The inadequate design and the lack of maintenance are among the factors that contributed to their unsatisfactory seismic performance. As well, the frequent deficient reconstructions, including those of about 25,000 rapidly repaired buildings damaged during the 1991–95 Homeland war, led to increased overall losses (Crnogorac 2021). Damage to municipal infrastructure (bridges, roads, drainage systems, and other utilities) and a number of ground failures (landslides, sinkholes, liquefaction of soils) were also observed.

By the end of February 2021, the economic losses were estimated at EUR 4.8 billion (Government of Croatia 2021). Sisak-Moslavina County is by far the most affected accounting for almost 79% of losses, while the remaining are distributed among the neighboring Karlovac, Krapina-Zagorje and Zagreb counties including the City of Zagreb itself that already suffered significant losses from the 2020 earthquake (Šavor Novak et al. 2020; Atalić et al. 2021).

This paper provides an overview of the 2020 *Mw* 6.4 Petrinja earthquake focusing on information collected during the field inspection and results stored in the GIS-based database (CCEE 2022). First, the specifics of the exposure in the epicentral area are explained. The seismological settings are discussed together with data on the series of earthquakes that hit the region (foreshocks, main shock and aftershocks). A detailed description of the organizational setup and activities related to the emergency response are provided next. The core of the paper is focused on the most typical damage to buildings and their spatial distribution.

2 Exposure in the epicentral area

The Sisak-Moslavina County is located in eastern Central Croatia and represents the third largest county in Croatia with 7.9% of the total surface (Fig. 1). With a population of 143,618, it is relatively sparsely inhabited with about 4% of the country's population and a density of only 31.5/km^2 (Croatian Bureau of Statistics 2021). It is also one of the least developed counties with most of the working age population concentrated in cities

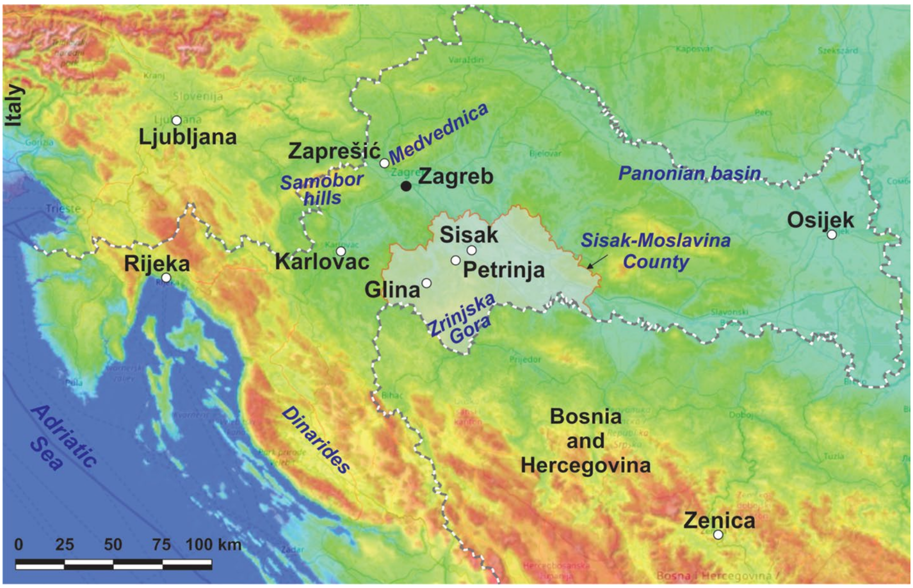

Fig. 1 Sisak-Moslavina County and neighboring regions

and high percentage of elderly people in rural communities (19.5% over 65). Despite the considerable post-war reconstruction efforts, a large portion of the internally displaced people has not returned home resulting in a significant number of abandoned houses. The economic activity, on the other hand, has recovered to some extent. The main economic sector is the food processing industry with 98% of total exports and as much as 53% of the county's agricultural land dedicated to organic farming activities developed in recent years (Sisak-Moslavina County 2021).

The construction practice in the affected area is similar to that in other parts of continental Croatia. According to the very rough estimation in the scope of the preliminary risk assessment of the county there are approximately 40% unreinforced masonry (URM), 30% confined masonry and 30% reinforced concrete buildings (Sisak-Moslavina County 2019). However, to date, there is no official inventory database in Croatia which will include construction material, age, footprint, structural system and occupancy category of the buildings. The effort to create digital databases is individual and mainly related to specific short-term projects and study areas (Atalić et al. 2019). The first comprehensive attempt in Croatia to propose a standardized typology for residential buildings was made in the scope of the regional EU-SERA project (http://www.sera-eu.org/en/home/). The smallest spatial unit for data aggregation was assumed at the municipality level. Among the inventoried approximately 70,000 residential buildings in the Sisak-Moslavina County, the most frequent are low-rise unreinforced masonry buildings (46%), followed by low-rise confined masonry buildings (27%) and low-rise (11%) and mid-rise (10%) concrete frames with infill walls (Crowley et al. 2018, 2019, 2020).

Traditional URM buildings are dominant in both urban centers of Petrinja, Glina and Sisak and in the rural areas. Most of the masonry buildings in the historic city centers are built in the late 18th and early nineteenth centuries of solid brick and lime mortar. They are classified either as individual cultural heritage or are protected being a part of the cultural and historic ensemble. The load bearing walls are continuous from the foundation to the attic and support the weight of the floor and roof structures without any confinement (Fig. 2a). They are typically up to two stories high with attic and are positioned in aggregates or as freestanding. The floor structure is made of timber joists oriented in the direction transverse to the longitudinal bearing walls. In some cases, the ground floor consists of brick cross and barrel vaults. The partition walls are also made of solid brick, whereas the roof structure is made of timber beams and rafters often without adequate stabilizing elements. The tall and massive chimneys are usually free standing from the attic floor level. Not adequately anchored to the main structure are also the traditional non-structural elements such as cornices, plasters and other decorations. As well, most of the buildings have been poorly maintained, contributing to significant deterioration of the materials and compromising the safety of the occupants and pedestrians.

The older URM multi-apartment buildings, frequent in the urban areas, have a semi-precast floor structures of reinforced concrete and masonry with girders and ring beams, the so-called "fert" structure slabs (Fig. 2b). The number of stories varies from two to four. The roof structure in these buildings is made of timber trusses without stabilizing elements. On the other hand, the confined masonry buildings with vertical and horizontal confining elements and semi-precast floor structures started appearing mostly after 1995, as part of the post-war reconstruction. According to the seismic regulations at the time (SFRY 1981), valid until the introduction of Eurocode for the design of masonry structures in 2007, it was not mandatory for low-rise buildings to use confined masonry instead of unreinforced masonry. In other words, masonry structures without vertical confinement elements were allowed for up to G + 2, ground floor plus two storey buildings, in seismic zone VIII and up

Fig. 2 City of Petrinja **a** URM buildings in the historic centre, **b** Multi-apartment masonry buildings, and **c** Single masonry and wooden residential buildings (Google Maps 2021, CCEE 2022)

to G + 3 in seismic zone VII (for the return period of 500 years), both of which cover most of the Sisak-Moslavina county. The seismic zones in the seismic hazard maps valid at that time were defined considering the maximum observed intensities according to the MCS scale.

Nowadays, confined masonry is the most common structural system for low-rise residential buildings.

In addition to URM and confined masonry buildings, in rural areas are typical the traditional wooden single-family residential buildings with one and rarely with two stories (Fig. 2c). They have a simple rectangular foot-print and the connection of the wooden walls is usually done with hardwood dowels. Often, they are accompanied by outbuildings, which are usually made of poorer material and structural quality.

Due to the inconsistency of the structural systems, part of the load bearing structures in residential buildings can hardly be classified into a single typology. The long exploitation period combined with multiple occupation phases and successive reconstructions and upgrades make distinguishing one typology category from another difficult. In some cases, buildings are with URM walls at the ground level only, while confined masonry walls are present at the first and upper floors. This peculiar feature is typical for buildings reconstructed or retrofitted after the Homeland war of 1990s. In this paper, we refer to these buildings as partially confined masonry typology. According to the official statistical data for the period from 1997 to 1999, about 25,000 housing units on the territory of Sisak-Moslavina County, mostly single-family houses, were subject to different levels of architectural modifications. The regulatory approach for rehabilitation at the time stated that the damaged buildings have to be restored to their original state as before the war allowing for structural improvements.

However, seismic design was generally not given attention. Rehabilitation was mainly carried out by installing the semi-rigid or rigid reinforced concrete floors in places where wooden joists were present and by converting part of the partition walls into load-bearing walls. In some places, vertical confinement was designed and executed, either cut into the existing walls or built in the corners of the existing walls, without intervening in the walls. In most cases, the vertical tie-columns were not systematically placed at all corners and around the larger openings, as it is required by current seismic standards. The new reinforced concrete floors were generally much heavier than the previous wooden floor systems.

In cases where there were the existing semi-precast fert floors, with load-bearing capacity in one direction, or the relatively thin reinforced concrete slabs, they were kept in their existing form, and depending on the side of the masonry walls, a vertical tie-column was installed into the masonry walls.

Concerning the steel structures, it should be mentioned that the structural steel is very rarely used in residential and commercial building stock in Sisak-Moslavina county. However, steel structures are present in the industrial facilities such as the mineral fertilizers plant in Kutina, the old oil refinery in Sisak and several industrial halls in the county.

3 Seismological overview

3.1 Regional seismotectonic settings

Croatia is located in the broader Africa-Eurasian tectonic plate boundary zone. Its geological structure and seismicity are defined by the convergent movement of the African plate towards the relatively stable Eurasian plate with the Adria microplate wedged between them. The Adria microplate has been largely consumed through collision and/or subduction that resulted in the formation and accretion of mountain chains (the Apennines, the Alps, the Dinarides, the Albanides, and the Hellenides) at the boundaries and remained undeformed in the central part, mostly under the Adriatic sea. The neotectonics in the area is defined by the ongoing convergent plate movement and the translation and counterclockwise rotation of the Adria microplate. As a result, the Dinarides contract through thrust and strike-slip faults. Further north-east, the continental part of Croatia was intensively influenced by the tectonic extension of the Pannonian basin linked to the geodynamics of the Alps and the Carpathians. For a more detailed description see the overview by Belinić et al. (2021).

The north-western part of Croatia lies in the interaction zone between the Alps, the Dinarides, and the Pannonian basin, on the border of the Adria microplate and the Eurasian plate. This is a basin-type area largely filled by Neogene and Quaternary deposits. These thick deposits overlay Mesozoic and Paleogene bedrock with breccias, conglomerates and limestone, followed by a layer of sandstones, shale and marls, and topped by sands, clay and gravels (Šumanovac 2010; Pollak et al. 2021). A few isolated mountains are composed of Mesozoic rocks. The faulting in this area is complex. The analysis of the earthquake focal mechanisms conducted by Herak et al. (2009) showed that the compressional tectonic stress is dominant and directed mainly N–S. Reverse fault systems striking NE–SW or E–W are characteristic for the northern and central part, e.g., Medvednica fault system, whereas faults in the western and southern part are mostly strike-slip directed NW–SE, e.g., Petrinja fault system. The seismic activity of continental NW Croatia is described as moderate with rare occurrence of strong events, typical for intraplate seismicity. However, it is unevenly distributed as the most active is the western margin, in the transitional zone between the Dinarides and the Pannonian basin: from the Medvednica-Zagreb epicentral area, through the Kupa Valley epicentral area to the south-east of the Banja Luka epicentral area in Bosnia and Herzegovina. Based on the earthquake catalogue analysis, Ivančić et al. (2018) concluded that for the continental part of Croatia current long-term average moment release rate is equivalent to one M_W 5.0 earthquake per year or one M_W 6.4 earthquake per century.

3.2 Petrinja—Zrinska gora seismic zone

The December 2020 Petrinja series of earthquakes occurred within the Petrinja—Zrinska gora seismic zone, sometimes also referred to as the Kupa Valley seismic zone (Ivančić et al. 2002, 2006, 2018; Markušić and Herak 1999). One of its most important seismological features is the Petrinja fault system identified with HRC027 in the European Database of Seismogenic Faults (Basili et al. 2013). The maximum expected moment magnitude there is estimated at M 6.5. The strongest known event was recorded on October 8, 1909, with an estimated epicenter 10 km north of Pokupsko. With surface wave magnitude M_S 5.8 and epicentral intensity of I_0 = VIII EMS scale (Herak and Herak 2010; EMS—European macroseismic scale), the quake was responsible for loss of two lives, a number of injuries and significant physical damage. The strong shaking also caused occasional appearance of soil liquefaction, mud volcanos and sand craters. According to the Croatian Earthquake Catalogue (CEC; described in Herak et al. 1996 and regularly updated), three additional earthquakes with local magnitude $M_L \geq 4.0$ occurred more recently in the same epicentral area. The strongest was on 10 September 1996 with M_L 4.5 (I_{max} = VI MSK, Medved-Sponheuer-Karnik macroseismic scale), just south-west of Petrinja. For the wider Petrinja–Zrinska gora epicentral area and the period 1997–2015, Ivančić et al. (2002, 2006, 2018) report only a few light earthquakes. Two of them worth mentioning occurred about 30 km south-southwest of Petrinja in the Zrinska gora area: on 27 January 1997 with M_L 4.3 (I_{max} = IV MSK) and epicentre near Trnovac Glinski, and on 2 October 2014 with M_L 4.0 ($I_{\max}$ = V–VI MSK) and epicentre between Divuša and Unčani, at the Croatia–Bosnia and Herzegovina border.

The probabilistic seismic hazard analyses conducted for local soil conditions type A for Petrinja and Glina townships predict a horizontal peak ground acceleration (*PGA*) of 0.11 g for a return period of 225 years, and 0.15 g for 475 years (Herak et al. 2011; Herak 2020). However, since both Petrinja and Glina are situated mainly on recent alluvial sediments, it can be expected that the ground surface *PGA* will be higher. No detailed microzonation studies have been performed so far in this region.

3.3 Petrinja 2020 series of earthquakes

The 2020 Petrinja series of earthquakes began with moderately strong foreshocks on 28 December 2020 with epicenters near Strašnik, about 5 km to the south-west of the downtown Petrinja: M_L 5.1 at 6:28 CET, M_L 4.6 at 7:49 CET and M_L 3.8 at 7:51 CET. They were followed by many weaker earthquakes. The main shock struck the next day on 29 December 2020 at 12:19 CET with epicenter near to those of the foreshocks and estimated magnitudes M_L 6.2 (Croatian Seismological Survey 2021a; Herak and Herak 2023) and M_W 6.4 (EMSC 2021). The main shock had a focal depth of about 8 km (Herak and Herak 2023). The maximal macroseismic intensity was estimated as I_{max} = VIII EMS (heavily damaging; Croatian Seismological Survey 2021b). However, as a reminder, this estimation has a cumulative character: it is difficult, maybe even impossible, to distinguish what would be the estimate of the mainshock's I_{max} if there were no significant foreshocks already causing damage and weakening of structures. The earthquake shaking was felt strongly throughout Croatia, Slovenia and most of Bosnia and Herzegovina, and was reported as felt in Austria, Slovakia, Hungary, Serbia, Montenegro, and Italy, and possibly even in Germany, Czech Republic, Romania, North Macedonia and Albania (EMSC 2021).

As reported in the preliminary report by Stipčević et al. (2021), 9,350 earthquakes with $M_L \geq 1.5$ were recorded in the period between 28 December 2020 and 29 March 2021 (Fig. 3). Most of the epicenters were located in a narrow, well-defined area along Hrastovička gora and the well-known Petrinja fault trending northwest-southeast. The strongest aftershock of M_L 4.9 (M_W 4.8) occurred on 6 January 2021 at 18:01 CET with the epicenter near Župić. A relatively small number of subsequent earthquakes occurred on the fault above the mainshock's hypocenter (the longitudinal profile A–A' in Fig. 3a), which suggests that most of the collected tension was released from that section during

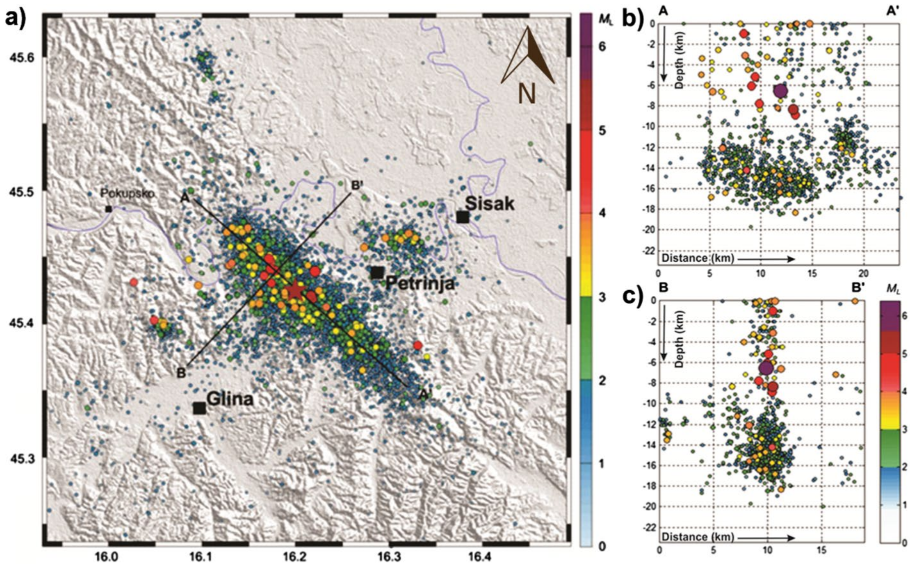

Fig. 3 The series of 9350 earthquakes with $M_L \geq 1.5$ occurred between 28 December 2020 and 29 March 2021: **a** plan view, **b** cross-section A–A' (longitudinal profile), and **c** cross section B–B' (transverse profile). The magnitude of the earthquakes is indicated according to the size of the circles and the color scales. The main shock is indicated with the dark red star (adapted from Stipčević et al. 2021)

the mainshock. The majority of the aftershocks occurred at depths between 10 and 18 km, below the main shock's focus. The transverse profile B–B' (Fig. 3c) clearly depicts a vertical fault. Stipčević et al. (2021) also reported coefficient $b = 0.9$ of the Gutenberg-Richter relation, which means that for a decrease in a unit of magnitude 7.9 times more aftershocks can be expected. In the first 13 days of the series, there were ten earthquakes with $M_L \geq 4.0$, and 76 earthquakes $M_L \geq 3.0$ (Dasović et al. 2021).

The focal mechanism of the main shock was obtained by polarization of the first P-wave onset. It shows a subvertical (dip of 89°) right fault, strike-slip with a horizontal displacement (rake of -175°) along the northwest-southeast fault (strike of 139°) (Stipčević et al. 2021). This is consistent with the results obtained from the inversion of seismic moment tensors by global seismological centers given by EMSC (2021). This means that the southwestern fault wing shifted to the northwest and the northeastern wing to the southeast. This finding coincides with the spatial distribution of earthquake foci outlining the activated part of the fault and is confirmed with the results obtained with the InSAR method (Govorčin 2020; Ganas et al. 2021; Xiong et al. 2022). Stipčević et al. (2021) reported that most of the stronger quakes show similar focal mechanisms, however, a few of them located to the northwest of the main group, have formed on reverse faults. The focal mechanisms show the direction of the main axis of the pressure stress field in the SSW-NNE direction confirming the dominance of the compressional stress in this area (Fig. 3).

The application of the InSAR methods in computing of the line-of-sight displacement and modelling of the fault parameters by uniform slip inversion were performed by Ganas et al. (2021) and Xiong et al. (2022). The line-of-sight displacement was estimated at approximately 40 cm and inversion indicate a relatively small fault plane surface was activated, about 8 km × 5 km with a large mean slip of about 3 m without reaching the ground surface. The fault strike was estimated at 129°, dip between 76° and 87° and rake of 176°. The relatively shallow depths, for the main shock combined with the estimated slip larger than what can be expected for the magnitude explain in part the widespread damage observed in the epicentral zone.

3.4 Ground motions

The December 2020 series of earthquakes in the Petrinja–Zrinska Gora epicentral zone was recorded by the strong motion digital network of seven stations located within the Zagreb metropolitan area. This network has also been instrumental in providing valuable strong ground motion data for the March 2020 *Mw* 5.4 Zagreb earthquake, of utmost importance for the consecutive risk reduction research activities: seismic hazard assessments, dynamic analyses in the time domain, performance-based engineering analyses, etc. All stations are located NNW from Petrinja within a narrow backazimuthal range at epicentral distances varying between 45 and 60 km. Definite vertical stratigraphy underneath these stations is still not well known, however, for most of them it is reasonable to assume the relatively conservative soil type C, $V_{S,30} = 180–360$ m/s (Miklin et al. 2019).

The processing of the strong motion records was conducted by Prevolnik (2021). Herein are presented data from the main *Mw 6*.4 event recorded at the QUHS station with epicentral distance of $R_{epi} = 48$ km. Figure 4 presents the time series of the processed acceleration, velocity and displacement of all three components (EW, NS and Z). The accelerogram typically shows the primary P-wave is the first signal to arrive followed almost immediately by the secondary S-waves. The much slower surface waves with lower frequencies arrive a few seconds after the onset of the seismic shaking indicating the strong motion

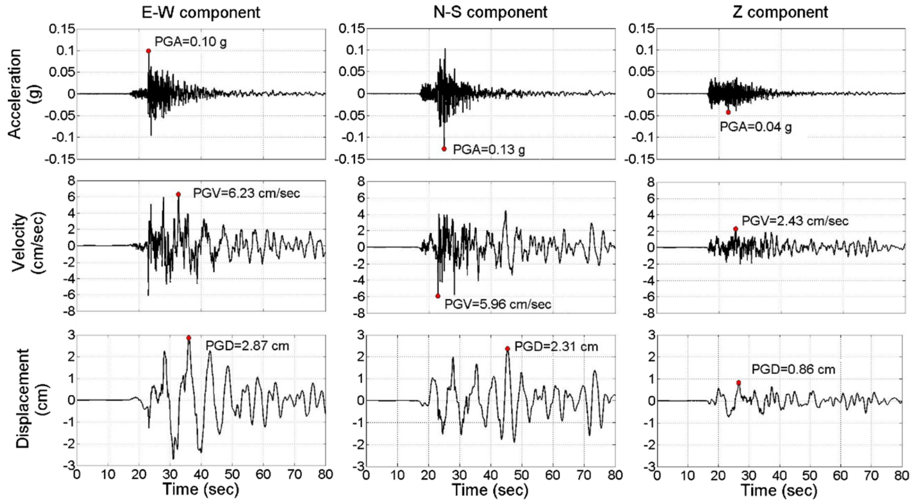

Fig. 4 Petrinja earthquake *Mw* 6.4 of 29 December 2020, the QUHS station records 48 km form the mainshock: processed acceleration, velocity and displacement time series of the horizontal E–W (left), horizontal N-S (middle) and vertical Z (right) component with maximal values indicated in the figures by red dot. Soil type on the location of the station QUHS according to EC8 is assumed to be type C (based on the results presented in the study Miklin et al. 2019)

phase. The measured peak ground acceleration is $PGA = 0.13$ g recorded on the NS component. To assess approximately the input motion parameters at the engineering rock level, defined as reference soil type A, a first-hand deconvolution of the recorded surface ground motion time histories was conducted. The EC-8 amplification factor for the elastic response spectrum of type 1 on soil type C which is assumed to be on the location of QUHS station (based on the results presented in the study Miklin et al. (2019)), and short period range, $F_S = 1.15$, yields a $PGA_{rock} = 0.11$ g. For comparison, the seismic hazard map of Croatia at the location of the QUHS station gives a similar $PGA_{rock} = 0.12$ g for a return period of 95 years. In general, such peak values are below the threshold for potentially damaging earthquakes, however, the December 2020 Petrinja earthquake caused damage in the Zagreb metropolitan area as well.

Zagreb suffered the most damage from the 5.4 magnitude earthquake that occurred 9 months before the Petrinja earthquake (described in detail in Šavor Novak et al. (2020); Atalić et al. (2021). A considerable number of buildings, especially the traditional masonry ones, were damaged. At the time of the Petrinja earthquake, the post-earthquake retrofitting of buildings in Zagreb had not yet begun in the larger scope. The Petrinja earthquake had a much lower PGA (about 2 times lower) compared to the Zagreb earthquake at the Zagreb site. But even as such, it had very unfavorable effects on the already damaged buildings in Zagreb. Many of these buildings were already unusable and were evacuated because of significant damage, which was exacerbated by the series of Petrinja earthquakes.

The Fourier amplitude spectra and the 5% damped pseudo-acceleration (*PSA*), pseudo-velocity (*PSV*) and displacement (*SD*) response spectra for the three components of the main event recorded on the QUHS station are shown in Fig. 5. It can be seen in Fig. 5a that the frequency content has a decreasing trend of the spectral amplitudes with increasing frequency due the rapid attenuation of the high frequency motion components with distance. For all three components, the highest amplitudes are found around 4–4.5 Hz, particularly the N-S

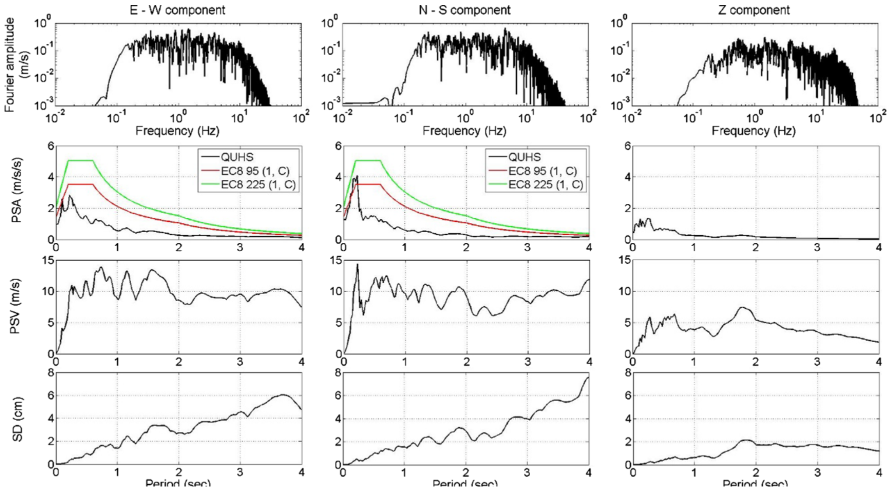

Fig. 5 Petrinja earthquake *Mw* 6.4 of 29 December 2020, the QUHS station records (48 km from the maishock's epicenter): **a** Fourier amplitude spectrum, **b** 5% damped pseudo-acceleration response spectra (PSA) and EC8 type 1 elastic horizontal response spectra for the soil type C (assumed to be on the location of the station QUHS based on the results presented in the study Miklin et al. 2019) associated with 95 and 225 years return period according to Herak et al. (2011, 2022) studies, **c** 5% damped pseudo-velocity response spectra (PSV) and d) 5% damped displacement response spectra (SD). Left: horizontal E-W component. Middle: horizontal N-S component. Right: vertical (Z) component

component, and between 1–2 Hz. Figure 5b shows higher pseudo-acceleration spectral amplitudes in the N-S direction, in particular for periods lower than 0.5 s, whilst below 0.3 s these values are comparable or even exceed EC8 type 1 elastic horizontal response spectra derived for soil type C based on the seismic hazard map of Croatia for 95 years return period, but not overcoming values defined for the 225 years return period. As expected, the amplitudes of the vertical component are in the range of 50–75% of the spectral acceleration values of the two horizontal components. Figure 5c shows pseudo-velocity spectral amplitudes having increasing trend up to periods of 0.3 s, and then slightly varying around the value of 10 m/s on both horizontal components and around 5 m/s on vertical one. The 5% damped displacement response spectra in Fig. 5d indicate similar trend of increasing amplitudes with period for the horizontal motions, whereas the vertical spectral displacements start to decrease for periods > 1.8 s.

In addition to data from the strong motions recorded within the Zagreb metropolitan area discussed above, the USGS-PAGER team generated approximate shakemaps of the main shock (USGS 2022). The predicted value of *PGA* at the ground surface in the epicentral area was almost 0.5 g, whereas in Zagreb the *PGA* was estimated as 0.1–0.15 g. Although their method implicitly takes into account a very rough site amplification based on the regional topographic slope used as a proxy for the $V_{s,30}$, these results coincide well with the recorded data.

4 Emergency preparedness and response

4.1 Organizational setup

The Government of Croatia is currently in the process of overhauling the whole community preparedness system, in particular the creation of effective strategies and building up resilience for improved disaster risk management. This was one of the major commitments made upon joining the European Union in 2013. In 2014, the Croatian Government initiated the process to achieve the predefined risk management objectives. Subsequently, the major disaster risks in Croatia were identified and a firsthand evaluation was carried out, including the seismic risks (Atalić and Hak 2014). The process continued and in 2018 the risk management capacities were assessed and an update of the disaster risk evaluation for Croatia was made (Atalić et al. 2018). Because of its administrative, cultural and economic importance, particular focus was put on the risk evaluation of what-if earthquake scenarios for the capital city of Zagreb. The assessment results demonstrated that the earthquake scenario with a low likelihood of occurrence would cause catastrophic consequences, which run beyond the criteria adopted from the European Commission, and that the seismic risk is high. Indeed, these consequences exceed the potential losses from other hazards identified in Croatia (Government of Croatia 2019). The systemic framework for seismic risk reduction appears to be well established, especially through the Croatian Platform for Disaster Risk Reduction within the Directorate for Civil Protection of the Ministry of Interior. However, because of lack of allocated resources, only a few of the activities were directed to risk reduction and prevention, such as implementation of strategies for seismic retrofitting of the aged building stock and of critical infrastructures.

There are positive examples at the local level as well. For instance, the Office of Emergency Management of the City of Zagreb (EMO) organizes various activities related to post-earthquake situations (drills, equipment acquisition, etc.) and funds studies to examine various issues related to earthquake risk reduction (Atalić et al. 2014, 2018, 2019, 2020, 2021). As well, following a number of years of collaboration on disaster risk studies, exercises and seminars, a Crisis team was established on voluntary basis in March 2020 after the Zagreb earthquake. It mainly consists of experts from the Faculty of Civil Engineering supported by the city EMO, the Directorate of Civil Protection and especially the Croatian Chamber of Civil Engineers (Šavor Novak et al. 2020). By linking researchers, professionals and intervention units, collaboration was achieved to combine different knowledge and expertise with the aim of providing optimal response tailored to the local settings and capacity constraints.

4.2 Emergency response

4.2.1 The foreshock

On Monday, December 28 at 6:28 a.m. CET, a magnitude *Mw* 4.9 foreshock occurred with sufficient force to be felt throughout Croatia. At the time, Croatia was still under partial COVID-19 lockdown and restrictions on movement between counties were enforced a few days earlier. Only a small number of expert teams could therefore be mobilized in the beginning by the Civil Protection to provide essential emergency services, such as ensuring the safety of critical buildings, evacuating the elderly and providing medical assistance. In parallel, the geo-information platform ArcGIS Online was activated for updating and storing the collected field information in a dynamic database. Towards the end of the first day, the building damage assessment system was set up.

4.2.2 The main event

On Tuesday, December 29, early in the morning, the systematic inspection of residential buildings, family houses and essential facilities began. However, at 12:19 CET the main *Mw* 6.4 event took place. Beside the casualties, this devastating earthquake caught several experts within vulnerable and already damaged buildings. Immediately after the earthquake struck, all inspection work was halted, and engineers were recalled using mobile phones (WhatsApp) and the damage assessment app. All teams gathered at the central headquarters to reorganize and reassess the situation. At the same time, all available operational forces of the civil protection system and emergency services across Croatia were immediately dispatched to Sisak-Moslavina County to provide assistance.

Among the many heavily damaged structures, priority was given to secure the unusable buildings and to urgently continue the inspection of the essential facilities and critical infrastructures, part of which had already been inspected the previous day. Health care facilities, kindergartens, schools, administrative buildings, police and military facilities, and shelters for temporary accommodation of the population were the first to be inspected. Transportation facilities (roadways, railways and bridges) were also inspected and geotechnical and geological experts were deployed as numerous ground failures had been reported. As of the beginning of January 2021, between 300 and 400 experts were engaged in building inspections on a daily basis. A total of 1,700 engineers and architects participated in the overall process of damage and usability assessments.

To better cover the populated areas and to efficiently organize the available first responders, smaller headquarters were formed in Glina and Sisak in addition to the central headquarters in Petrinja. Citizens were able to report damage by phone, email, and online through the ArcGIS Survey Poll web form. The total number of validated damage reports was about 50,000, of which about 80% were related to buildings within the Sisak-Moslavina County. The remaining reports came from inspections performed in the neighboring counties and the City of Zagreb. All damage reports were completed using the promptly adjusted app Collector for ArcGIS application, which was feeding a layer in the Esri Geospatial Cloud supported by the company GDi (www.gdi.net) in a way that the information was immediately visible to field experts. The digital capture of inspection attributes in the field allowed for rapid data collection. This proved extremely important, especially in the first days, since all priorities, i.e., emergency interventions, road rehabilitation, sheltering, etc., were determined on a daily basis based on the submitted reports.

4.3 Damage and usability forms

The assessment of the building damage and usability was one of the top priorities of the emergency response. This information was important because decisions with major consequences had to be made related to estimations of housing needs (evacuation, shelters, accountability), undertaking protective actions (threats, warning, preventing unauthorized access, securing damaged structure), planning field teams (number of first responders, qualifications, use of special equipment), conducting preliminary evaluation of economic losses, etc. Since each community has its own characteristics, resources and demographics, the quality and reliability of the obtained information depended, first of all, on the system preparedness for conducting field inspections, clearly defined methodology and prior expertise of qualified experts.

The first inspection form for rapid damage assessment of buildings in Croatia was the one developed in the aftermath of the Zagreb earthquake. It was initially based on the preliminary studies on earthquake risk reduction and on the experience of Italian colleagues (Atalić et al. 2014, 2018, 2019, 2020, 2021; Baggio et al. 2007). During the initial building inspections, the basic form has undergone certain adjustments considering the local construction practices and the valuable feedback by the inspection teams. In parallel, a detailed methodology and expert guidelines for an on-site building inspection including description and categorization of typical damage with examples from the Zagreb earthquake were published (Uroš et al. 2020). The evaluation of the building usability is based first of all on the severity of damage to structural elements. The non-structural elements are only of secondary importance and are used to confirm or infer indirectly potential impacts to the structural stability. Other threats and potential hazards have also to be taken into account, such as frequency and magnitude of the ongoing aftershocks, common elements with neighboring structures (e.g., walls), location, occupancy and importance of the building, etc. Accordingly, each inspected building is tagged with green (U—usable), yellow (PN—temporarily unusable) or red (N—unusable) color. Subcategories were also introduced to provide additional information on the actions to be taken related to the use and the stability of the building: U0—without damage; U1—usable without limitation; U2—usable provided short-term counter measures; PN1—temporarily unusable, detailed inspection required; PN2—unusable, important interventions required; N1—unusable due to external risks, and N2—unusable due to severe structural damage. The inspection form also classifies the extent of damage according to the European Macroscale EMS-98 (Grünthal 1998), where: negligible damage corresponds to damage state level I (DS1), slight to moderate damage to levels II (DS2) and III (DS3), and heavy to very heavy damage corresponding to levels IV (DS4) and V (DS5).

4.4 Challenges

Overall, the emergency management and planning were improved considerably in the months preceding the Petrinja earthquake. The experience acquired following the Zagreb earthquake was crucial for the emergency response in the Sisak-Moslavina County. One of the main issues was the danger of COVID-19 transmission due to a large number of people and intervention units arriving from elsewhere. To minimize the health risk, an emergency vaccination campaign was initiated for all intervention units and population, starting on 2 January 2021.

Among the difficulties encountered during the field inspections were the multiple inspection requests for the same building, difficult-to-access remote villages, areas with poor or no GSM signal, hostile reactions from residents unfamiliar with inspection methods, contradictory and confusing media information, etc. There were also problems associated with the mobilization of experts through the system of Civil Protection, accommodation of the relatively large number of experts into the improvised system, insurance for the first responders and vehicles, financing and procurement of the necessary field equipment (helmets, vests, hammers, stickers, etc.), management of the donations, etc. At the end of the emergency response process (March 2021), 10 experts were injured and 5 cars were damaged.

5 Seismic losses

5.1 Observed damage

Extensive damage to buildings was widespread in Petrinja, the nearby towns of Glina and Sisak, as well as throughout the rural settlements of the Sisak-Moslavina County. Based on the inspection results, the most damaged buildings were of unreinforced masonry (URM), followed by confined masonry (CM), while the reinforced concrete (RC) structures (consisting of approximately equal parts of infilled frames and dual systems) sustained much lesser damage (Fig. 6a). The building category referred to as "other types", which accounts for 7% of damaged buildings in this figure, includes traditional wooden houses as well as mixed structural systems, e.g., wood and URM or partially confined masonry (Fig. 25). However, it was observed that the latter building category was frequently classified as the more resistant CM in the inspection forms. The confusion resulted because the inspection form did not provide explicit option for this peculiar typology, however, specific to a relatively large number of buildings. Due to the insufficient time and accelerated training, only a part of the experts managed to recognize these buildings as "other types". As mentioned in Chapter 2, the partially confined masonry buildings disregard standard engineering practices and seismic regulations resulting in critical structural deficiencies. Furthermore, it should be mentioned that no damage to steel structures was reported, also the inspection of the industrial steel structures of the oil refinery in nearby town Sisak and the industrial plant in Kutina, located about 40 km from Petrinja, did not reveal any significant structural damage caused by this earthquake.

Another important statistical indicator correlated to the usability of buildings is the year (period) of construction. The graphs shown in Fig. 6b clearly indicate that buildings built before 1930 have sustained the most significant structural damage. The damage percentage decreases gradually for more recent structures due to the improvement of the construction practices with the introduction of the new and improved construction standards and seismic regulations.

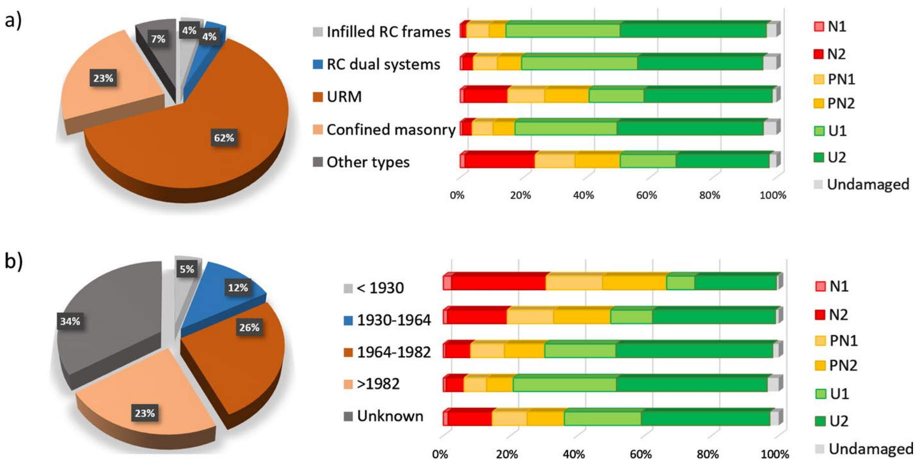

Fig. 6 Data on building usability assessments in the affected area with respect to: **a** most common structural systems, and **b** period of construction (CCEE 2022)

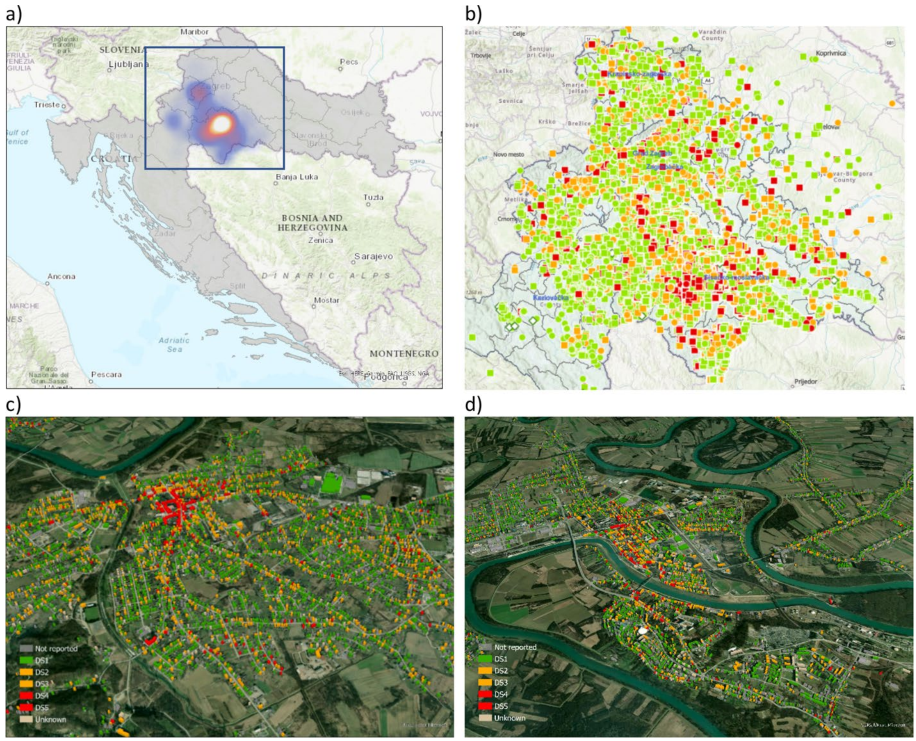

Fig. 7 Building inspection results: **a** heatmap of the affected area, **b** usability assessments in the central Croatia, **c** spatial distribution of structural damage in Petrinja according to EMS-98 scale, **d** spatial distribution of structural damage in Sisak according to EMS-98 scale. The usability states in (**b**) are indicated with: green—usable, yellow—temporarily unusable, red—unusable. The damage states in (**c**) and (**d**) are negligible damage DS1, slight to moderate damage DS2 and DS3, and heavy to very heavy damage DS4 and DS5. (CCEE 2022)

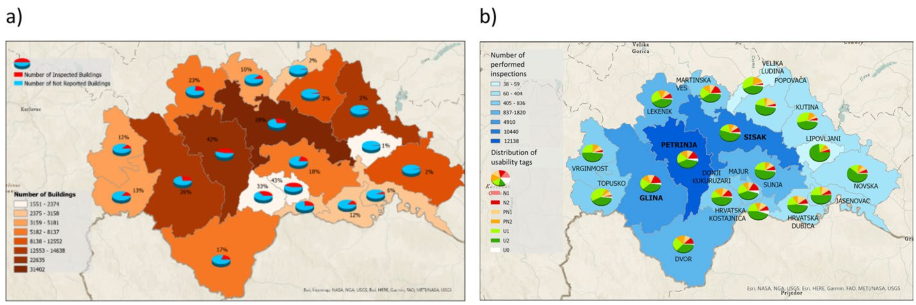

Fig. 8 Building inspection results for Sisak-Moslavina County: **a** percentage of inspected buildings; **b** usability assessment results by municipalities (CCEE 2022)

Figure 7a presents the heatmap of the affected area, while the usability assessments for the most affected region of the Central Croatia (marked with blue rectangle in Fig. 8a) are given in Fig. 7b. The spatial distribution of damage in the towns of Petrinja and Sisak

Table 1 Results of building usability inspections in all affected counties (CCEE 2022)

	Results of building usability inspections							
	U0	U1	U2	PN1	PN2	N1	N2	Sum
Number	829	10,981	22,081	5058	5678	492	4881	50,000
Percentage	2%	22%	44%	10%	11%	1%	10%	100%

Table 2 Results of damage assessments according to EMS-98 scale in all affected counties (CCEE 2022)

	Results of damage assessments according to EMS-98 scale						
	DS1	DS2	DS3	DS4	DS5	n/p	Sum
Number	29,078	9741	4371	2759	685	3366	50,000
Percentage	58%	19%	9%	6%	1%	7%	100%

according to the inspection results is shown in Fig. 7c and d. It clearly points out the concentration of damage in the historical centers where mostly URM buildings built in the late 18th and first half of the nineteenth century are located.

The systematization of the characteristic damage was made addressing parameters which correlate best with the degree of damage. Beside the building typology (structural system), age and the seismic excitation (e.g., intensity of the seismic shaking, its frequency content and duration, local site conditions), important considered parameters were the building specific structural and dynamic properties, which significantly affect its dynamic response and incurred damage. Such are the geometry of the structure (plan disposition and height), distribution of the mass and stiffness, materials used for construction and their quality (e.g., deterioration due to aging, exposure to water, etc.), and the quality of the construction itself and of reconstruction(s) made throughout the building life. It was observed that the quality of the connection joints between the different structural elements represents important factor for ensuring the ductile behavior of the structure. When not adequately anchored, these joints were responsible for local failures and compromised the load-bearing capacity of the structural elements, even before the ultimate strain of the connecting element was attained. This was a common observation in URM buildings with timber joists and without confining elements. The location and exposure of the building to the immediate surroundings was also considered. This included the position of the building within the aggregate of buildings (townhouses), the potential interaction between adjacent buildings, and the structural type, materials, floor heights and distribution of façade walls of the adjacent buildings.

By the end of March 2022, a total of 50,000 inspections were conducted in all affected counties, covering approximately 13,000 km^2 what is more than a fourth of the country's territory (Fig. 7a and 7b). According to Table 1, overall, 5,373 buildings were red-tagged (N1 1% and N2 10%), 10,736 yellow-tagged (PN1 10% and PN2 11%), 33,062 green-tagged (U1 22% and U2 44%), while in 829 inspected buildings no structural damage was observed (U0 2%). Regarding the damage according to EMS-98 scale presented in Table 2, there were 29,078 buildings graded DS1, 9,741 DS2, 4,371 DS3, 2,759 DS4, 685 DS5, and 3,366 inspections that did not provide damage assessment according to the EMS-98 scale.

In the Sisak-Moslavina County only (Fig. 8), 38,320 inspections were conducted with 4,745 red-tagged buildings (N1 1% and N2 11%), 8,397 yellow-tagged (PN1 10% and PN2

12%), 24,475 green-tagged (U1 19% and U2 45%), while 703 inspected buildings showed no damage (U0 1%). In Fig. 8a, the pie chart shows the ratio of inspected buildings to all buildings in the municipalities of Sisak-Moslavina County, while the total number of buildings in a municipality is indicated by shades of brown. In Fig. 8b, the pie chart presents the distribution of the usability assessment results in performed inspections, while the total number of performed inspections in the municipalities is indicated by shades of blue. Obviously, due to its proximity to the epicenter, the municipality of Petrinja was the most affected. Out of the 12,138 buildings inspected there, 15% were red-tagged, 24% yellow-tagged, and 59% green-tagged.

5.2 Economic losses

In cooperation with the World Bank, the government prepared a "Rapid Damage and Needs Assessment" document for the affected area (Government of Croatia 2021). The document considers the Sisak-Moslavina County, the three neighboring counties and the City of Zagreb. The estimates in the document are based on about 86% of the inspections carried out in the first two months following the earthquake, by the end of February 2021. The international DaLA methodology for the assessment of earthquake impacts in economic terms was applied with certain adaptations to the local context. In the DaLA method, damages and losses are represented with performance indicators before and after the earthquake. The damage is determined as the monetary value of fully or partially destroyed assets (reconstruction costs), while losses are estimated based on the changes in the flows of goods and services due to the absence of the destroyed assets, but also include operating costs and measures taken to reduce the resulting losses until the destroyed assets are rebuilt. Accordingly, the total damage for Petrinja earthquake is estimated at 4.12 billion euros, while the temporary losses amount to 714 million euros. According to the data of Croatian Bureau of Statistics (2023) gross domestic product (GDP) of the Republic of Croatia in 2020 amounted to 50.46 billion EUR. Therefore, the estimated total economic losses (including the indirect losses) of 4.8 billion EUR correspond to approximately 10% of the national GDP.

The most affected area was the epicentral Sisak-Moslavina County, with 80% share of the sustained physical damage and 75% of the losses. Damage data for the Sisak-Moslavina County indicate that the most affected was the housing sector (2.22 billion euros), followed by culture and cultural heritage (260 million euros), health (118 million) and education (109 million euros) sectors. Significant damage and losses were reported in the economic, agricultural and infrastructure sectors (1.16 billion euros), as well as damage due to geological failures (liquefaction and sinkholes). It is important to note that much of the damage and losses are associated with the cultural heritage buildings, where more than 120 individually protected heritage buildings were heavily damaged (red-tagged). In the culture and cultural heritage sector, by far the higher losses are related to the reconstruction of the sacral buildings.

On the other hand, the overall recovery and reconstruction costs were estimated at 8.4 billion euros (Government of Croatia 2021). As much as 56% is associated with the costs for the housing sector. These costs are much higher than the damage and losses estimated above, because of the consideration of the *build back better* principle in the calculation. It is emphasized that these estimates were made based on the physical consequences of the earthquake only, without taking into account all the activities needed to fully revitalize the affected area. The process of prioritization in the reconstruction and recovery strategy is certainly one of the key factors, and it was noted that the housing and economic sectors should be of the highest priority to prevent further internal and external emigration from the affected area. The planned activities of the Government strategy can be divided into different timeframes with short- and long-term goals. The safety of the population and its needs, including housing, access to health care, education, and social protection, are among the priorities to achieve in the short-term and to lay the foundations for sustainable development and resilience of the entire community in the long-term. The short-term financial support for the economy is necessary in order to secure current jobs and enable their further progress through the introduction of modern technologies, as they are both critical to retain people in place. In this regard, it is important to revitalize the agricultural business, which mostly consists of small family farms engaged mainly in livestock production. All these activities are planned to lead towards the reduction of not only the seismic risk, but also risks from other natural and man-made hazards, e.g., consequences from climate changes. Overall, ensuring social protection, rebuilding the transport and communication infrastructure links, the energy sector, water management and protection, and access to public facilities and public administration, should lead the recovery activities.

6 Damage to essential facilities

6.1 Health care facilities

The health care sector was obviously critical for the emergency response and recovery efforts, in particular considering the fact of the insufficient number of health institutions and their scattered distribution across the Sisak-Moslavina County. Most of the existing health care facilities were built in the late 19th and early twentieth centuries, with as much as 80% built before the introduction of the first seismic building code in 1964. Built without adequate resistance to earthquake loads, these buildings sustained different levels of damage, and a minor disruption in their work was the cause for important difficulties for patients and personnel. It was therefore important to ensure that hospitals continue providing services due to the number of injuries and new COVID-19 patients. However, assessing the usability of hospitals appeared a complex and very demanding task often including measures of protecting or transferring patients outside the disaster area in anticipation of additional quakes and risking deterioration of the health-care.

As a result of the series of earthquakes, a total of 90 buildings belonging to community health centers were damaged to a certain degree with 13 buildings assessed as temporarily or permanently unusable. The earthquake also directly affected 76 hospital buildings. Of these, 15 buildings were assessed as unsafe for patients and personnel and temporarily or permanently unusable. A significant portion of the equipment and installations in hospital buildings were damaged. In addition, six health care facilities remained temporarily unusable and two were assessed as permanently unusable. As well, 27 pharmacies were damaged, two of which were assessed as unusable. Most of the observed damage was associated with the massive free-standing brick chimneys and wooden roof structures. As a result, the gas flow was suspended and the heating and hot water supply had to be cut off, which meant closure of the entire building. In many cases, due to minor damage to the roof, cornices, decorative elements and plaster, the usability was reduced to only a part of the building, although the structure itself was not threatened.

An example of a heavily damaged hospital during the earthquake is "Dr. Ivo Pedišić" in Sisak, the central point of the health care system in the affected area. The most damage was sustained by the buildings of the internal clinic, pediatric department, neurology and otorhinolaryngology which were assessed as unusable. Since most buildings were built as unreinforced masonry, all the classic mechanisms of collapse of structural and non-structural elements were observed. A significant portion of the load-bearing walls were damaged, and unsupported parts such as gable walls and chimneys collapsed. The internal clinic and the administrative buildings are shown in Fig. 9a and b. Both were assessed as heavily damaged beyond repair. Damage to the pediatric building built in 1959 was assessed as moderate to severe, and the entire building together with the departments of pediatrics, neurology and otorhinolaryngology was yellow-tagged (temporarily unusable; Fig. 9c).

The Special hospital for chronic diseases in Petrinja was moderately damaged and was evaluated as temporarily unusable pending a detailed engineering inspection. Damage to gable and partition walls is given in Fig. 10a. Another important health care facility in

Fig. 9 Sisak, damage to buildings in the health sector, Hospital "Dr. Ivo Pedišić": **a** Internal clinic, **b** Administrative building, and **c** Pediatrics building (CCEE 2022)

Fig. 10 Petrinja, damage to buildings in the health sector: **a** Special hospital for chronic diseases and **b** Health center in Petrinja (photos: private collection of authors and courtesy of Tina Nikolić, Joning d.o.o.)

Petrinja, the Community Health center also suffered heavy damage (Fig. 10b). Most of the load-bearing walls were significantly damaged and the chimneys collapsed. The building has a reinforced concrete ribbed slab which prevented the development of out-of-plane failure mechanisms. Partition walls were severely damaged and a number of them collapsed. Following a detailed inspection, it was decided to demolish the building.

6.2 Educational facilities

Among the educational facilities, 70 preschool institutions and kindergartens, 192 schools and 10 higher education buildings were affected by the earthquake. Fortunately, because of the public holiday, the schools were closed on the day of the main event and not many children were in the kindergartens. Approximately 40% of the affected buildings are located in the Sisak-Moslavina County, among which 13 school buildings were heavily damaged and completely unusable (red-tagged) with three of them individually protected as cultural heritage (Government of the Republic of Croatia 2021). As a consequence, more than 3,000 pupils had to be relocated to other schools. Two examples of damage to educational facilities are given in Fig. 11. The Petrinja Primary school, a valuable URM heritage building, sustained extensive damage with significant damage to load-bearing walls, and collapse of gable walls, a number of spandrels and of partition walls. The roof structure also partially collapsed. Despite the recommendation of the field inspection experts to demolish the building, it is currently under retrofit because of its high cultural value.

The Faculty of teachers' education in Petrinja was constructed in the 1960s. The building is of irregular footprint and height and consists of three large interconnected wings. The load-bearing structure consists of a system of peripheral RC frames and interior URM walls. The floor structure is made of RC slabs and beams connected to the vertical load-bearing system. The building suffered light to locally moderate structural damage. The

Fig. 11 Petrinja, damage to buildings in the educational sector in: **a** Primary school, and **b** Faculty of teachers' education (CCEE 2022)

masonry spandrels sustained severe damage, whereas the load-bearing walls were only slightly to moderately damaged, particularly those supporting the stair landings. Cracks in the concrete floor structure were limited to contacts with a significant change in structural geometry. In several classrooms, ceiling layers collapsed completely or partially, and all partition walls were severely damaged due to the exceedance of shear force.

6.3 Other public buildings

In addition to health facilities and educational buildings, many other public buildings, such as libraries, community centers, courts, government buildings, etc., were also severely damaged. Among them was the Petrinja City Hall, an individually protected heritage building (Fig. 12). This URM heritage building has suffered severe damage to practically all walls, vaults, and arches, and has visibly disturbed geometry evidenced by the deformation of the exterior load-bearing walls and separation of contacts among perpendicular walls.

7 Damage to sacral and heritage buildings

Severe damage occurred to numerous sacral buildings, mainly churches and chapels, many of them listed as heritage monuments. Besides being mainly built with construction practices from the past, these masonry structures are distinct in all other respects. Each of them has its own architectural and aesthetic characteristics, e.g., footprint, height, spans, choice and quality of the materials, etc. According to data collected by the Diocese of Sisak (Sisak archdiocese 2021), the earthquake caused damage to 39 churches, 17 of which suffered

Fig. 12 Damage to buildings in the public sector, Petrinja City Hall (CCEE 2022)

severe structural damage or collapse, to 24 chapels and 13 parish houses. More than half of the sacral buildings were listed as individually protected cultural monument. A few examples of damage to sacral objects are given in Figs. 13 and 14.

Heavy structural damage to church bell towers and load-bearing walls revealed to be the most common damage type (Fig. 13). Severe structural damage and, in some cases, collapse were result of the lack of anchors that would prevent the walls from buckling outwards and from collapsing inwards. Severe damage was often observed to roofs requiring urgent repair where possible. Also, frequent damage and particularly severe cracking were observed on many vaults and arches.

Figure 14a shows the church of St. Nicholas and St. Vid in Žažina, which suffered considerable structural damage caused by collapse of the bell tower. Part of the roof of the main nave also collapsed as did the vaults supporting the roof structure. Unfortunately, the organist of the parish lost his life under the rubble in this church. One of the most valuable and beautiful Baroque churches in continental Croatia is certainly the parish church of St. Mary Magdalene in Sela near Sisak (Fig. 14b). Both towers of the church, the entrance portal, the lintels and walls, and the dome were severely damaged. Urgent protective measures were therefore implemented including the erection of supporting scaffolding to alleviate any threat of collapse of arches and external walls, and stabilization of both towers. The third example shown here is the parish church of the Assumption of the Virgin Mary in Gora. This church was destroyed and rebuilt several times over the centuries. The last facsimile reconstruction of this early Gothic Templar church of carved stone blocks was completed in 2015 without any modern materials and techniques. The authentic reconstruction work was based on extensive archaeological and conservation-restoration research (Miletić and Valjato Fabris 2014). However, the project obviously lacked awareness of the seismic risks, and the new church sustained extensive damage, the tower collapsed together with several arches and part of the roof structure (Fig. 14c).

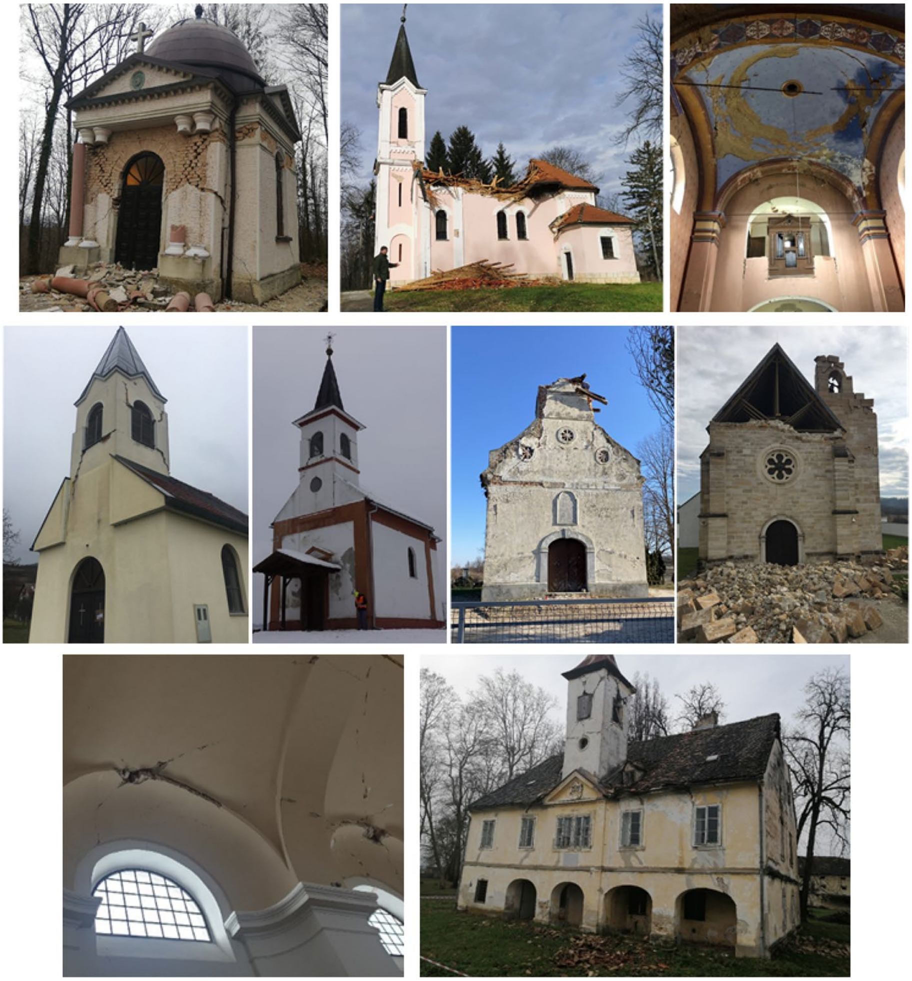

Fig. 13 Examples of damage to sacral buildings (CCEE 2022)

Due to the significant number of damaged buildings following the March 2020 Zagreb earthquake and insufficient time and resources, a large portion of those buildings remained without proper preventive measures and reconstruction. When the December 2020 Petrinja earthquake hit the region, it caused additional damage to structures already damaged by the previous earthquake. An example of such progressive damage is the church of St. Catherine in the Upper Town Zagreb, whose vaults extensively damaged during the previous earthquake collapsed together with parts of the ceiling (Fig. 14d).

In addition to the sacral buildings, many other heritage buildings have also suffered significant damage. The historical core of the town of Petrinja was hit the hardest, with damage ranging from very severe to devastating. Most of the heritage buildings in the center of Petrinja suffered structural collapse due to their proximity to the epicenter and had to be demolished due to widespread damage and total loss of structural stability. Where possible, emergency measures were taken to stabilize the structure and remove severely damaged

Fig. 14 Damage to sacral buildings: **a** Church of St. Nicholas and St. Vid in Žažina, **b** Church of St. Mary Magdalene in Sela, **c** Church of the Assumption of the Virgin Mary in Gora, and **d** Church of St. Catherine in Zagreb after Zagreb earthquake (left) and after Petrinja earthquake (center and right) (photos: courtesy of Sisak archdiocese 2021; CCEE 2022; and Martina Vujasinović, 2022)

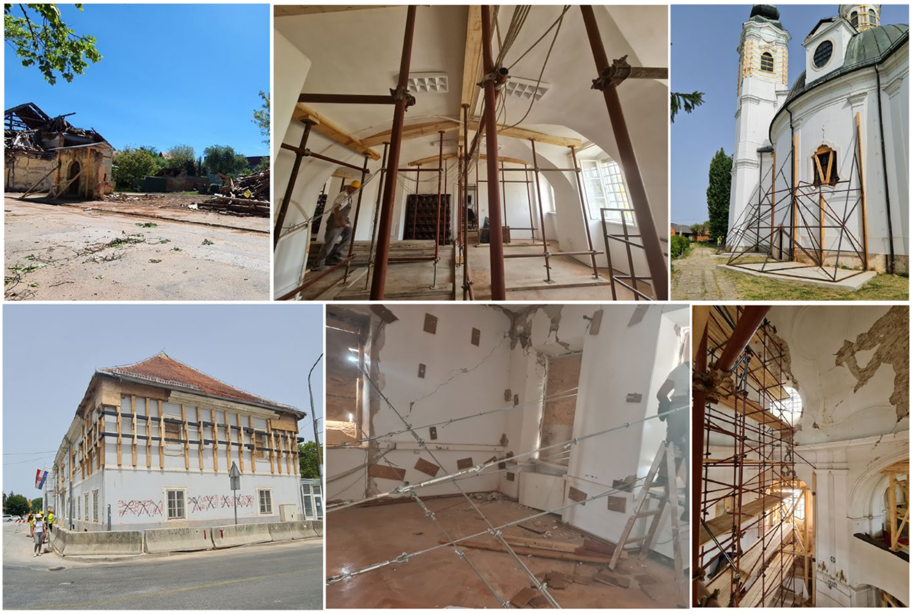

Fig. 15 Demolition and emergency measures in heritage buildings

parts and debris (Fig. 15). In some cases, only portals were left, while the rest of the building had to be demolished and later reconstructed in facsimile.

8 Damage to residential buildings

8.1 Damage to masonry buildings

The buildings that suffered most structural damage are undoubtedly the older unreinforced masonry buildings (URM), almost two-thirds of the total. They are located mainly in the historical centers of Petrinja, Glina and Sisak and scattered across the rural areas. Quantitatively, most of the damage was suffered by residential one and two storey with interconnected load-bearing walls and wooden floor structure or vaults at the ground floors. Failure of the structural walls in masonry buildings was caused mainly by out-plane seismic action due to exceedance of the load-bearing capacity and/or to overturning of the wall due to poor connections with the orthogonal bearing walls, or less frequently to their in-plane failure. The various irregularities of the building plan and height were observed to contribute to large displacement demands on the structural elements at the edges away from the center of stiffness.

Generally, the area of the masonry walls in these buildings ranges from 5–10% of the gross floor area in both principal directions, while the fundamental periods in both principal direction amount to 0.1–0.15 s. As stated before, buildings built before 1964 were not designed for seismic loads, while from 1964 to 1982 (SFRY 1964) the lateral force coefficient was between 0.0375 for the seismic zone VII and 0.075 for the zone VIII. After 1982 and the introduction of the new seismic code (SFRY 1981), the lateral force coefficient was between 0.05 for the seismic zone VII and 0.1 for the zone VIII.

The local-specific fragility curves were not developed for these buildings. However, in the national risk assessment carried out in 2018 (Atalic et al. 2018), the curves for low rise URM buildings were defined using the macroseismic approach (Lagomarsino and Giovinazzi 2006) in accordance with the RISK-UE project (Milutinovic and Trendafilovski 2003), what was described in more detail in (Atalic et al. 2021). Following the same approach, the fragility curves were defined for the most damaged URM typologies in Petrinja earthquake.

Damage classification was made according to EMS-98. The mean damage grade function was calculated on the basis of the macroseismic intensity and the vulnerability index. The vulnerability index for M34L type (low-rise URM buildings with RC slabs) is estimated to 0.72, while for the M31L type (low-rise URM buildings with wooden floors) it is 0.84. The damage probability matrix corresponding to the mean damage grade for successively increasing intensities was developed. This step was carried out assuming that the damage distribution at each intensity level follows the beta function where, a = 0.0, b = 6.0, t = 8.0 and parameter r is given by equation $r = t\left(0.007\mu_D^3 - 0.052\mu_D^2 + 0.2875\mu_D\right)$ (Giovinazzi and Lagomarsino 2004).

The fragility curves are shown in relation to the EMS98 intensity. Conversion to PGA was not carried out, as there were no data on the recorded PGA in the epicentral area.

From Fig. 16, it may be observed that for the intensity VIII EMS there is about 7% probability of no damage, 30% of negligible to slight damage, 36% of moderate damage, 21% probability of substantial to heavy damage, 6% probability of very heavy damage and almost no probability of collapse for the low-rise URM buildings with RC slabs.

For low-rise URM buildings with wooden floors, there is about 1% probability of no damage, 13% of negligible to slight damage, 30% of moderate damage, 34% probability of substantial to heavy damage, 19% probability of very heavy damage and about 3% probability of collapse.

Regarding the damage according to EMS-98 scale which was presented in Table 2 for all inspected buildings, if we analyze only URM buildings (62% of all inspected buildings according to Fig. 6a), the results are relatively similar. There were 16,534 buildings graded DS1 (53.5% of all URM buildings), 6,827 DS2 (22%), 3,387 DS3 (11%), 2,146 DS4 (7%), 471 DS5 (1.5%), and 1,523 inspections (5%) that did not provide damage assessment according to the EMS-98 scale.

Out of all inspected URM buildings, approximately 93% (28,857) distinguished between the flexible and stiff floor structures.

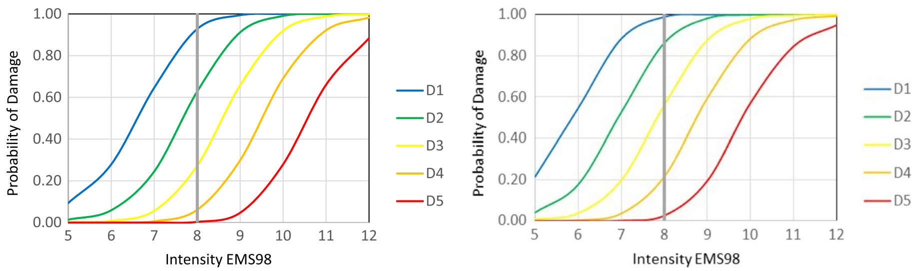

Fig. 16 Fragility curves in intensity for buildings of M34L type (left) and M31L type (right)

For URM buildings with stiff floors (approximately 60% of the 28,857 URM buildings with specified floor structure), there was 64% of buildings graded DS1, 20% DS2, 7% DS3, 4% DS4, 1% DS5, and 4% of inspections did not provide damage assessment according to the EMS-98 scale.

For URM buildings with flexible floors (approximately 40% of the 28,857 URM buildings with specified floor structure), there was 41% of buildings graded DS1, 26% DS2, 16% DS3, 11% DS4, 2% DS5, and 4% of inspections did not provide damage assessment according to the EMS-98 scale.

Direct comparison with the fragility curves is not possible for several reasons. The first one is that there should be data on the total number of URM buildings in the affected area. Unfortunately, such data does not exist as the census form includes only dwellings, and not the buildings or structural material and system. The other reasons why the results of the fragility curves give higher probabilities of damage is that it was assumed that intensity for all affected area was VIII, what is not true, and further analyses are needed, which are beyond the scope of this paper, to get more reliable results.

8.1.1 Out-of-plane failure

The predominant failure mechanism during the Petrinja earthquake was the out-of-plane failure, with serious consequences for global stability and threat to people's lives. Similar finding was reported based on observations of URM buildings failures during the past earthquakes in Croatia (Atalic et al. 2021). Namely, URM structural systems characterized with poor connections of the timber joist floor and roof structures with the bearing walls, often suffered out-of-plane failure due to the lack of horizontal and vertical confining elements and inadequate connections between orthogonal walls (Fig. 17a). In most cases, the ground floor bearing walls remained almost undamaged, indicating that the in-plane load-bearing capacity of the walls was not reached, as opposed to the stories above. The relatively low vertical loading, usually only G + 2 stories and an attic, combined with the higher vibration modes initiated the development of the out-of-plane mechanism in the upper floors. The main causes of the frequent failure of the gable walls was the insufficient connection between orthogonal walls and lack of stabilization and anchors combined with the low vertical loading. In turn, the failures of attic gable walls and facade walls at the upper floors caused destabilization and often collapse of the roof structures.

8.1.2 In-plane failure

On the other hand, exceedance of the in-plane bearing capacity in load-bearing walls was observed in masonry buildings confined with rigid floor structures that contributed to the box-like behavior. The shear mechanism in the bearing walls is manifested with typical diagonal cracks accompanied by cracking at joints owing to the poor quality of the mortar. The extent of damage concentrated on the ground floor indicates that the first mode dominates the dynamic response (Fig. 17b). Despite the relatively low lateral load capacity of masonry buildings, this confirms their moderate ductility due to the strong nonlinear behavior that includes stiffness changes due to cracking. The introduction of adequate diaphragm interconnecting the load-bearing elements, where installed, provided a favorable load distribution resulting in increasing of the building's global resistance to seismic loading. Although details of the connection between the confining

Fig. 17 Damage to unreinforced masonry buildings: **a** out-of-plane failure mechanisms, **b** in-plane failure mechanisms (CCEE 2022)

floor structure and the bearing walls are still not precisely known, field observations showed that, in such cases, the minimum requirement to prevent failure due to an out-of-plane mechanism has been met.

Fig. 18 Typical damage: In-plane wall failures and pounding effect (CCEE 2022)

Fig. 19 Damage to URM family houses including a collapse due to irregularity in elevation (left) and combined in-plane and out-of plane failures due to lack of vertical confinement (centre and right) (CCEE 2022)

8.1.3 Combined in-plane and out-of-plane failures

As well, there was also a number of URM buildings that sustained combined in-plane and out-of-plane failures. The impacts included cracks in short columns, overturning of walls, especially attic gable walls, and major damage to walls in the corners due to the lack of vertical confining elements.

8.1.4 Pounding effect

Another specific type of damage was observed in URM buildings constructed in aggregates. Namely, cases where no adequate gaps were left, the adjacent buildings were exposed to pounding effects. This was particularly pronounced in adjacent buildings with different dynamic characteristics, e.g., floor heights, which in turn contribute to out-of-phase vibration. (Fig. 18).

8.1.5 Damage to family houses

The highest number of damaged buildings belongs to residential single-family buildings, almost two-thirds. Many of those buildings were rapidly reconstructed after the

Fig. 20 Damage to (partially) confined masonry with significant structural deficiencies family houses (CCEE 2022)

1991/95 Homeland war, frequently without any standards for construction. The fact that most of those buildings performed relatively well during the earthquake suggests that some improvements were made, such as the construction of rigid diagrams. However, there are also cases of severe damage and even collapses of these buildings. As can be seen in the Figs. 19 and 20, the occurred damage resulted mainly due to construction defects, such as irregularities in elevation usually due to the addition of another storey, lack of vertical confinement, poor quality of materials and often inadequate structural details disregarding any construction codes.

On the other hand, the regular confined masonry buildings suffered mostly light to moderate damage. The most common damage patterns included damage to roofs, overturning of chimneys and gable walls, and damage to partition walls. In addition, moderate structural damage to load-bearing masonry walls was observed less frequently, mainly in the corners of openings or in masonry piers between openings where no vertical confining elements are present (Fig. 21).

Fig. 21 Damage to confined masonry family houses (CCEE 2022)

Fig. 22 Damage to roof structures and staircases (CCEE 2022)

8.1.6 Roof structures

The most common damage to roof structures was concentrated to collapse of chimneys, gable walls, and other cantilevered elements (Fig. 22). Cases were also observed where more severe structural damage occurred due to collapse of the bearing walls beneath, lack of stabilization elements, and the traditional poor maintenance and aged materials. During the strong motion shaking, the roof system load redistribution capacity becomes unstable as the timber elements show visible displacements or get out of bearing. Such damage has a significant impact on the entire roof structure, which very often requires complete reconstruction.

8.1.7 Staircases

The staircases were frequently damaged, whereas non-structural damaged was mostly related to the separation of the elements. More severe structural damage included the separation of the staircase at the junction with landings (Fig. 22 right).

8.1.8 Significant damage in the broader epicentral region

It is interesting to present herein the impacts to a few multi-storey residential masonry buildings in Zaprešić, a town located more than 60 km from the epicenter (Fig. 23). The causes of the relatively heavy and unexpected damage are still not known. As no damage to foundations or soil failure could have been identified, the high damage could be attributed to inadequate details in the construction and/or to the potential amplification of the seismic shaking as a result of local effects encountered by the seismic waves on their way towards the location. Preliminary results of earthquake simulations for the Petrinja earthquake suggest a potential channeling of the seismic waves in the area, located between the Samobor hills and Medvednica Mt., a phenomenon which increases the shaking intensity (Stipčević et al. 2021). As well, Zaprešić is situated in the lowlands between Sava and Krapina rivers

Fig. 23 Damage to multi-storey residential buildings in Zaprešić, located more than 60 km from the epicenter (CCEE 2022)

where deep soft alluvial deposits may trap the incoming seismic waves (basin edge effect) whose amplitude may increase with decreasing thickness of the unconsolidated sediments. Soil-structure resonance phenomena may also be considered as one of the reasons for the observed damage.

8.2 Damage to reinforced concrete buildings

Compared to the other structural types, damage to reinforced concrete structures was observed on a much smaller scale. The most frequent type of damage in these structures were cracks in the plaster and appearance of shear cracks in masonry infill walls as a result of the stiffness and deformation incompatibility between the walls and reinforced concrete frames. Rarely, brittle fractures in columns with insufficient transverse reinforcement and concentrated bending cracks in contacts between beams and bottom and top of columns, accompanied with spalling of concrete, were observed (Fig. 24a).

The absence of transverse reinforcement is characteristic of construction until 1964 and even later until 1981, when the first modern seismic codes were introduced that considered the ductility of joints and the prevention of brittle failure. Until then, the transverse reinforcement in the columns served mainly to connect the longitudinal reinforcement, and it was not considered in the load-carrying capacity because the horizontal seismic loads were not very high. Since the seismic forces were much lower according to the regulations of the time, it was not even necessary to provide the columns with

Fig. 24 Typical damage to RC building: **a** brittle fractures and **b** bending cracks in columns (CCEE 2022)

transverse reinforcement. Similarly, beams at that time usually had bent longitudinal reinforcement to resist shear forces from vertical loads, but not from earthquakes when cyclic loads are involved. Moreover, the transverse reinforcement was regularly of small diameter (6 or 8 mm) and was not properly overlapped to prevent buckling of the longitudinal reinforcement.

Figure 24b shows the structure of the bathing area building in Petrinja, which has only a ground floor. It is a relatively slender reinforced concrete frame structure. Due to earthquake, typical bending cracks appeared at the bottom and top of the columns. They are not wide and dangerous and there were no signs of yielding or bending of the concrete or crushing of the plaster.

8.3 Rural buildings

Traditional rural buildings are widespread across the Sisak-Moslavina County. Most of the observed damage was minor confirming their fair to good seismic performance exceeding that of the common URM buildings. The major advantage of these structures is in the light-weight wooden structural elements with joints with capacity to dissipate energy (Fig. 25a). Structural damage was almost inexistent and, when such damage did occur, it was localized mainly to joints between the wooden elements. Nonstructural damage, such

Fig. 25 Rural buildings: **a** Traditional wooden houses; **b** Buildings of different materials, and **c** agricultural buildings (CCEE 2022)

as collapses of chimneys, fallen roof tiles, or failure of the brick side-walls generally did not endanger the structural stability. On the other side, inconsistency of structural materials and elements was often noticed. Combined with inadequate construction, the use of different materials with often poor quality contributed to increased damage to such buildings (Fig. 25b). The Petrinja earthquake has also damaged a large number of agricultural buildings of smaller dimensions built with low quality material and unprofessional construction methods (Fig. 25c).

8.4 Non-structural elements

Damage to non-structural elements was by far the most frequent including damage to chimneys, to different parts of the roof, such as cracking and occasional falling of overhangs, cornices and roof tiles, and to various decorative elements. Almost all 'baroque' buildings in the epicenter suffered severe damage in their non-structural elements. These include cornices and significant cracking visible in decorative elements. As well, in many residential buildings, partition walls were damaged due to inadequate thickness and slenderness, or became completely detached from the load-bearing wall and had to be removed to avoid risk of complete collapse (Fig. 26a left).

Fig. 26 Damage to non-structural elements: **a** failure of partition walls and plaster detachment, **b** toppling of the outer wall, toppling of the heavy tile stove, and hole in the floor structure due to chimney collapse (CCEE 2022)

On the flip side, the partition walls are important in dissipating the earthquake energy and preventing further damage. Thus, although they crack relatively rapidly in the first cycles of the strong earthquake motion, they still have a significant contribution in load distribution and energy dissipation.

Partition walls are generally built orthogonal to the main longitudinal walls which support the wooden joists. They are made of the same material as the main walls, that is, solid bricks. However, since they do not support the floor structure (as the floor structure is load-bearing in one direction parallel to the partition walls), they are called partition walls. In addition, they are much thinner than the load-bearing walls, but in the transverse direction there is a considerable number of them, and in the total area of the walls in the transverse direction they are often equally represented as the load-bearing walls. For this reason, they were significantly affected when the predominant direction of the earthquake was transverse. Their contribution to the initial stiffness of the building in this direction is considerable. They also play an important role in earthquakes of lesser magnitude, since they are practically a part of the load-bearing structure for the seismic action.

Cracks and detachment of plaster walls and ceilings (Fig. 26a right) from the inside as well as from the building facade were common in older buildings. More severe damage included the collapse of false ceilings. Damage was also observed to massive non-structural elements such as cantilevered concrete and masonry elements, as well as toppling of outer walls and rarely heavy tile stoves, which in some cases caused further damage (Fig. 26b).

Fig. 27 Comparison of damage to buildings in Petrinja following the foreshock (indicated with Dec 28th) and the main shock (indicated with Dec 29th)

8.5 Damage comparison between the foreshock and the main event

The post-earthquake investigation conducted in the hours following the *Mw* 4.9 foreshock of December 28, 2020, even of limited extent, revealed some typical damage patterns to masonry buildings. The foreshock generated mainly slight and rarely moderate structural damage. As expected, damage was associated with the weakest elements, especially to gable walls, most of which were separated from the load-bearing orthogonal walls and tilted or partially collapsed. Cracking was also common along the junction of the bearing walls with wooden joists and minor damage was reported to lintels and vaults, mostly with delamination of the plaster. Significantly higher impacts to buildings occurred during the main *Mw* 6.4 event of December 29, 2020. This was expected, since stronger ground motions produce higher damage. A brief visual comparison of the damage state of the same buildings following these two events is given in Fig. 27.

It can be seen in Figs. 27, that the foreshock produced only minor damage, such as limited cracks in load bearing walls and initial formation of the failure mechanisms. A rapid visual comparison of photos of the same buildings taken after the main shock, suggest that they now sustained progressive moderate to extensive structural damage and even partial collapse. In the first three cases of Fig. 27, further propagation of the already formed cracks can be observed which caused failure of the affected structural elements. However, this was not the case with the fourth structure (lower right corner). There, the original mechanism developed after the foreshock did not evolve further. At the same time, a new crack pattern materialized causing the formation of failure mechanism that led to excessive deformation and near collapse limit-state of the structure.

9 Conclusion

The *Mw* 6.4 earthquake in Sisak-Moslavina County of December 2020 caused significant damage to buildings, municipal infrastructure and people. Sadly, there were seven fatalities, many injuries and 15,000 displaced people. As expected, residential URM buildings were affected the most, including buildings in historic centers of Petrinja, Glina and Sisak, and poorly built family houses in rural areas. Many essential facilities were severely damaged, such as hospitals, schools, roads and bridges. The estimated economic losses related to direct physical damage amount to almost 4.1 billion euros. The total economic losses, including the indirect losses are estimated at 4.8 billion euros. The total costs for reconstruction, according to the build back better principle, and rehabilitation of the region are estimated at 8.4 billion euros. It is, however, highly likely that this cost projection will increase due to the recent sharp increase in the energy and material market prices.

In spite of the partial lockdown due to COVID-19 pandemics, more than 1,700 experts from all over Croatia and neighboring countries participated in the post-earthquake field inspections. A total of 50,000 field evaluations of damage and usability of buildings were performed with approximately one third of the inspected building being assessed as temporary unusable or unusable.

Inspection results indicate that, unlike the typical damage to buildings observed following the Zagreb earthquake of March 2020 that included mainly damage to non-structural components (e.g., chimneys, attic gable walls, decorative elements and architectural finishes), the series of earthquakes in the Sisak-Moslavina County produced considerably higher damage due to the higher magnitude of the seismic shaking, *Mw* 6.4 vs. *Mw* 5.4, and relatively softer local soil conditions. The unreinforced masonry buildings were by far the most impacted. The out-of-plane failure was the dominant failure mechanism, followed by the less frequent combined in-plane and out-of-plane failures. In most cases, masonry buildings confined with rigid diaphragms showed satisfactory seismic performance achieving box-like behavior and fulfilling basic function of maintaining integrity even in a state of significant damage. The heritage buildings also mainly made of masonry, sustained extensive damage with several structural collapses, particularly in the epicentral area. The emergency measures such as shoring, propping and tying were often implemented for security reasons. Unfortunately, many of those damaged buildings had to be demolished in the aftermath due to heavy damage and loss of structural stability. In a few cases, certain parts of the facade, such as the entry portal, were preserved to be later integrated in the facsimile reconstruction. The occurred damage in churches was particularly highlighted because many of them were heavily damaged and a number of important architectural and historical elements were lost forever. On the other hand, superior performance was observed in buildings designed according to seismic regulations.

Overall, the magnitude of human suffering, physical destruction and economic losses incurred by the Petrinja earthquake caught the authorities and the affected population unprepared. The lessons learned from the March 2020 Zagreb earthquake increased indeed the awareness to earthquake exposure and vulnerability in Croatia. However, the nine months period prior to the Petrinja earthquake was insufficient to improve the current level of preparedness for such events. Although in their first phase, the activities for the disaster risk reduction program are ongoing. There is a consensus among the Croatian society that this tragedy, which occurred in one of the least developed parts of Croatia, will give another impetus in enhancing the capacity to save lives, protect property and economy and preserve the environment.

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Declarations

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