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Lessons from the 2020 earthquakes in Croatia to improve the seismic performance of cultural heritage structures

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Following a brief review of relevant characteristics and impacts of the 2020 earthquakes in Croatia, the damage sustained by two cultural heritage buildings is described to illustrate the impacts on this type of structures. Several strategies are then presented for implementing an adequate rehabilitation of this type of structures. Finally, a few strategic recommendations are discussed that contribute for the development of a more efficient seismic risk management strategy that safeguards the integrity and authenticity of cultural heritage ahead of future earthquakes. The contents of this article are based on the discussions held during the meetings of the *Expert and Advisory Committee for the Structural Renovation of the Architectural Heritage in the Earthquake Stricken Areas of the Republic of Croatia* and on information gathered during a reconnaissance visit to the areas affected by the earthquakes, in July 2021.

Keywords: post-earthquake repair, structural damage, church, confinement, bracing, authenticity, values

Ključne riječi: poslijepotresna obnova, oštećenja konstrukcije, crkva, omeđenost, podupiranje, autentičnost, vrijednosti

INTRODUCTION

Earthquakes are well known for being one of the most damaging and destructive natural hazards with impacts that span across most sectors of society and a recovery process that can take a significant number of years. Among the impacted sectors, cultural heritage is often one that involves a longer recovery process, namely due to the inevitable challenges related with physically restoring and repairing culturally significant historic constructions following internationally accepted principles targeting the preservation of their authenticity and values in post-event scenarios¹.

On March 22, 2020, a magnitude M_w 5.4 earthquake occurred with an epicentre around 7 km north of the Zagreb city centre. Aside from the fatalities and injuries directly or indirectly caused by the earthquake², the earthquake caused damage to buildings and critical infrastructure (namely hospitals and schools). Some of the most affected buildings were located in the old city centre, including both the upper town and the lower town of Zagreb. Among those, several cultural heritage buildings were damaged to various degrees, including the Zagreb Cathedral or the Museum of Arts and Crafts. Later that year, on December 29, 2020, a magnitude M_w 6.4 earthquake occurred with an epicentre located around 3 km southwest of Petrinja, a town in central Croatia. As for the previous earthquake, there were also fatalities and injuries directly or indirectly caused by the earthquake³. In terms of damage, there were numerous heavily damaged buildings and structures, particularly in towns near the epicentre such as Petrinja, Glina and Sisak, which include several cultural heritage buildings, namely those that were part of the historic centre of Petrinja.

Following a reconnaissance visit to the areas affected by the earthquakes that was carried out in July 2021 in the context of the *Expert and Advisory Committee for the Structural Renovation of the Architectural Heritage in the Earthquake Stricken Areas of the Republic of Croatia* founded by the Ministry of Culture and Media (Ministry), the current article provides a brief review of relevant characteristics of the referred earthquakes and describes the damage observed in two cultural heritage buildings that were impacted. In addition, the article provides recommendations regarding the recovery and rehabilitation of damaged cultural heritage buildings, and discusses strategical measures that could be implemented to enhance earthquake preparedness for future events.

1 ICOMOS, 2017

2 SO, EMILY et al., 2020

3 MIRANDA, EDUARDO et al., 2021

Pregled saznanja o potresima u Hrvatskoj 2020. u svrhu unaprjeđenja seizmičkih svojstava konstrukcija građevina kulturne baštine

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Nakon kratkog pregleda relevantnih karakteristika i posljedica potresa 2020. godine u Hrvatskoj, opisana je šteta koju su pretrpjele dvije zgrade kulturne baštine kako bi se ilustrirali utjecaji na tu vrstu konstrukcija. Potom je prikazano nekoliko strategija za provedbu odgovarajuće sanacije takve vrste konstrukcija. Naposljetku, raspravlja se o nekoliko strateških preporuka koje pridonose razvoju učinkovitije strategije upravljanja seizmičkim rizikom kojom se štiti integritet i autentičnost kulturne baštine prije nastupanja budućih potresa. Sadržaj ovoga članka temelji se na raspravama održanima tijekom sastanaka *Stručno-savjetodavnog povjerenstva za konstrukcijsku obnovu graditeljske baštine na potresom pogođenim područjima Republike Hrvatske* te na podacima prikupljenima tijekom izvidnih posjeta područjima pogođenima potresima u srpnju 2021.

Ključne riječi: poslijepotresna obnova, oštećenja konstrukcije, crkva, omeđenost, podupiranje, autentičnost, vrijednosti

Keywords: post-earthquake repair, structural damage, church, confinement, bracing, authenticity, values

UVOD

Potresi su dobro poznati kao jedna od najštetnijih i najrazornijih prirodnih katastrofa čiji posljedice pogađaju većinu sektora društva, a proces oporavka može potrajati znatan broj godina. Među pogođenim sektorima, kulturna baština je često sektor u kojem se odvija dulji proces sanacije uslijed neizbježnih izazova fizičke obnove i rekonstrukcije kulturno značajnih povijesnih građevina prema međunarodno prihvaćenim načelima usmjerenim na očuvanje njihove autentičnosti i vrijednosti u scenarijima nakon razornih događaja.¹

Dana 22. ožujka 2020. zabilježen je potres magnitude $M_w=5.4$ s epicentrom oko 7 km sjeverno od središta

Zagreba. Osim žrtava i ozljeda koje je prouzročio izravno ili neizravno,² potres je prouzročio štetu na građevinama i kritičnoj infrastrukturi (konkretno: bolnicama i školama). Neke od najpogođenijih građevina nalaze se u staroj gradskoj jezgri, uključujući zagrebački Gornji i Donji grad. Među njima je nekoliko u različitoj mjeri oštećenih objekata kulturne baštine, uključujući Zagrebačku katedralu i Muzej za umjetnost i obrt. Kasnije te godine, 29. prosinca 2020., zabilježen je potres magnitude $M_w=6.4$ s epicentrom oko 3 km jugozapadno od Petrinje, grada u središnjoj Hrvatskoj. Kao i kod prethodnog potresa, bilo je žrtava i ozlijeđenih izravno ili neizravno prouzročenih potresom.³ U pogledu šteta, brojne građevine i konstrukcije teško su oštećene, posebice u gradovima u blizini epicentra poput Petrinje, Gline i Siska, među kojima je i nekoliko objekata kulturne baštine koje su dio povijesne jezgre Petrinje.

Slijedom izvidnog posjeta područjima pogođenima potresom u srpnju 2021. u okviru *Stručno-savjetodavnog povjerenstva za konstrukcijsku obnovu graditeljske baštine u potresom pogođenim područjima Republike Hrvatske* što ga je osnovalo Ministarstvo kulture i medija (Ministarstvo), u ovom članku daje se kratak pregled relevantnih karakteristika navedenih potresa te opisuje šteta uočena na dvjema pogođenim građevinama zaštićenima kao kulturna dobra. Uz to, u članku se daju preporuke o obnovi i sanaciji oštećenih objekata kulturne baštine te se raspravlja o strateškim mjerama koje bi se mogle provesti u svrhu unaprjeđenja pripravnosti za buduće potrese.

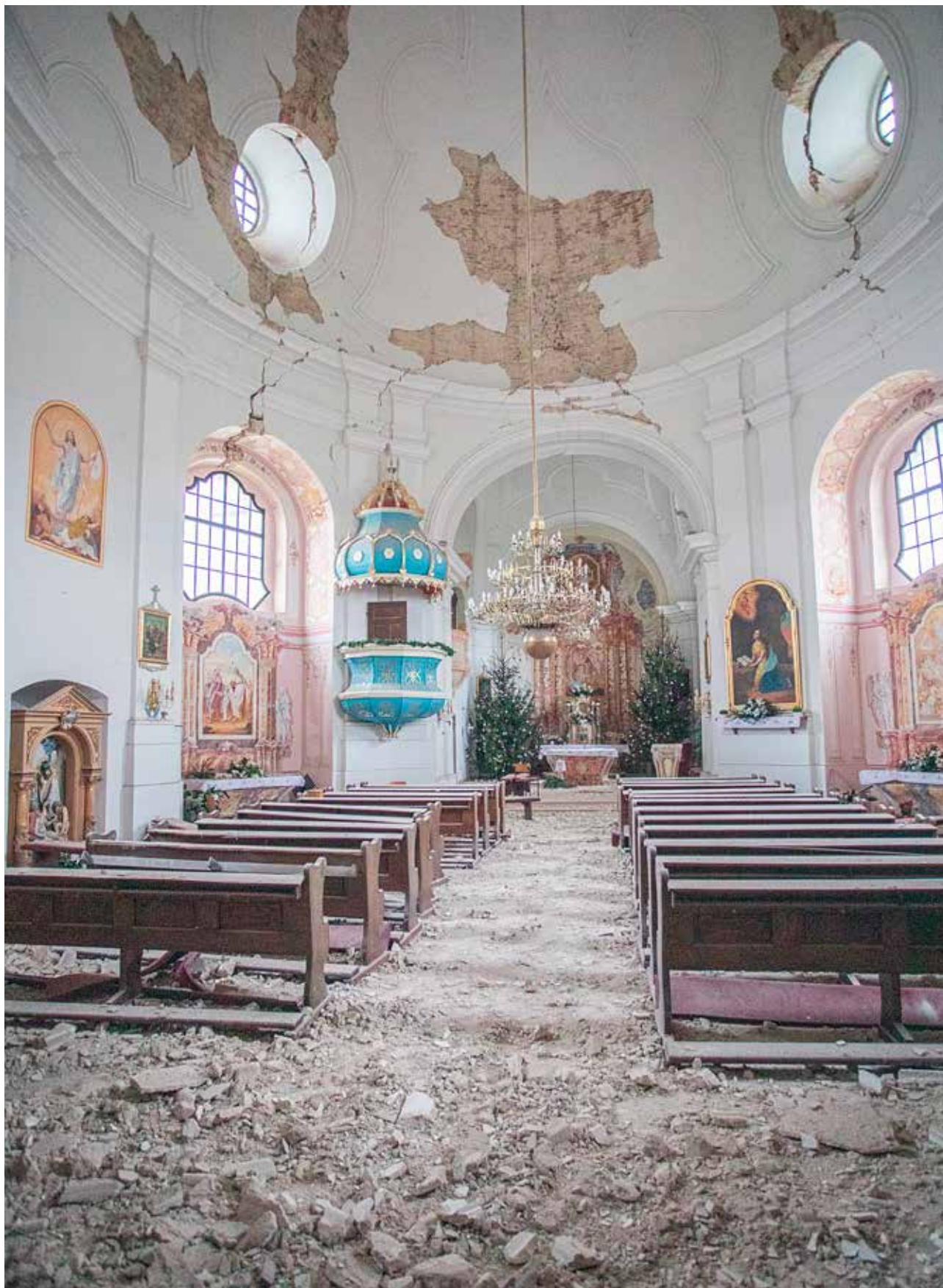
KRATAK OPIS RELEVANTNIH ZNAČAJKI POTRESA 2020. GODINE

U sljedećim odjeljcima nisu sadržani detaljni prikazi dvaju potresa i njihovih učinaka. Umjesto toga, obrađeni su određeni aspekti povezani s intenzitetom tih potresa koji

¹ ICOMOS, 2017.

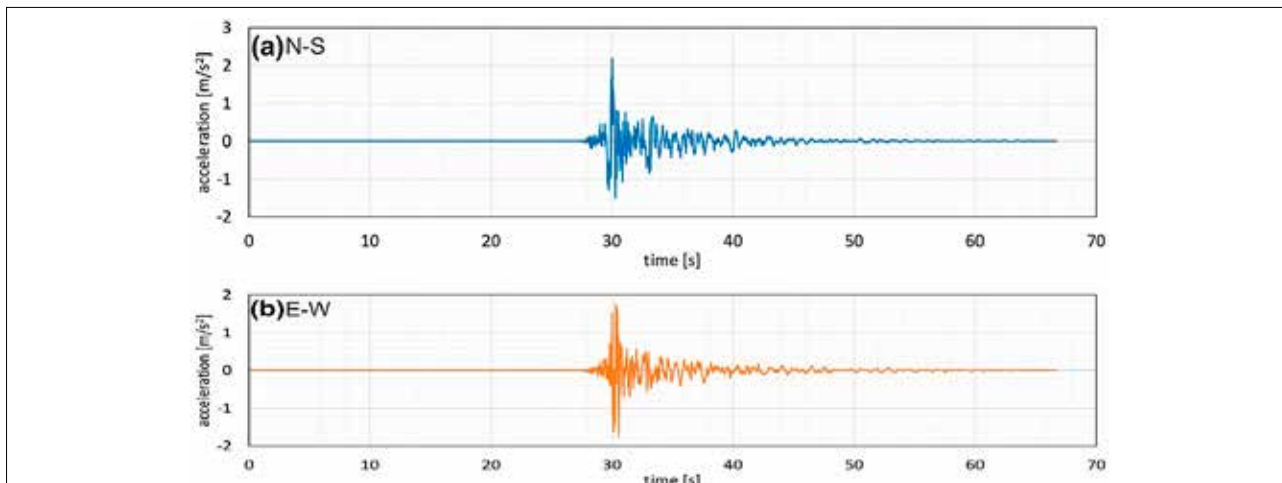
² SO, EMILY et al., 2020.

³ MIRANDA, EDUARDO et al., 2021.



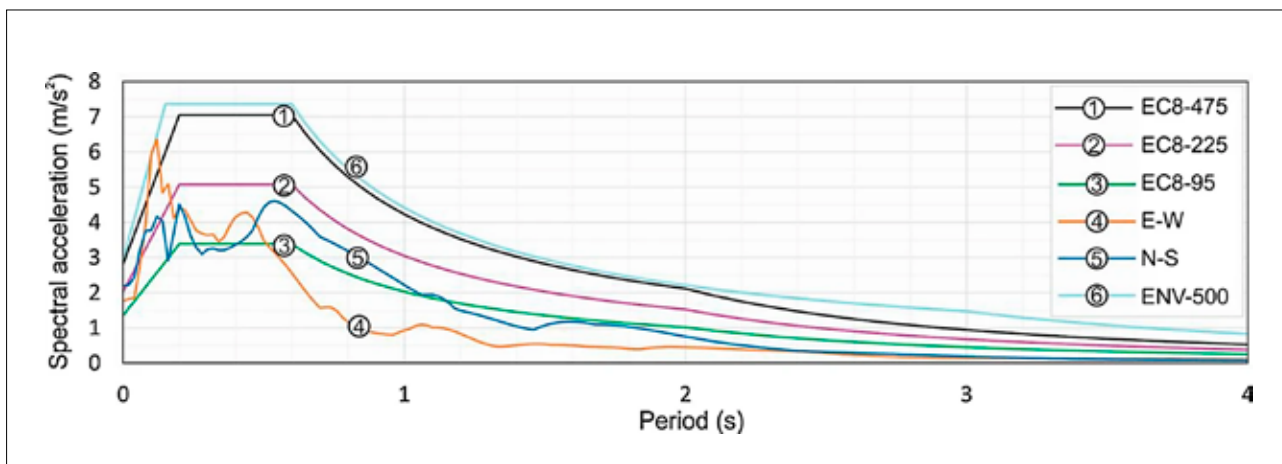
Interior of the Church of St. Mary Magdalene in Sela following the Petrinja earthquake, view towards the sanctuary (photo: Stjepan Vego, Sisak Diocese, December 2020)

Unutrašnjost crkve sv. Marije Magdalene u Selima nakon petrinjskog potresa, pogled prema svetištu (foto: Stjepan Vego, Sisačka biskupija, prosinac 2020.)



1 Accelerograms of the March 2020 earthquake recorded by the station located at the Zagreb Emergency Management Office: North-South (N-S) (a) and East-West (E-W) (b) horizontal directions (adapted from ATALIĆ et al., 2021).

Akcelerogrami potresa u ožujku 2020. koje je zabilježila postaja smještena u zagrebačkom Uredu za upravljanje u hitnim situacijama: vodoravni smjerovi (a) sjever-jug (N-S) i (b) istok-zapad (E-W) (prilagođeno prema ATALIĆ et al., 2021.).



2 5%-damped response spectra of the N-S (blue) and E-W (orange) recorded components along with the corresponding Eurocode 8 (EC8) elastic response spectra for return periods of 95, 225 and 475 years. The elastic response spectrum of the former Croatian Seismic Code ENV-500 for a return period of 500 years is also displayed (adapted from ATALIĆ et al., 2021).

Spektri odgovora za 5-postotno prigušenje za zabilježene komponente N-S (plavo) i E-W (narančasto) zajedno s odgovarajućim elastičnim spektrom odgovora iz Eurokoda 8 (EC8) za povratna razdoblja od 95, 225 i 475 godina. Prikazan je i elastični spektar odgovora bivšega hrvatskog seizmičkog propisa ENV-500 za povratno razdoblje od 500 godina (prilagođeno prema ATALIĆ et al., 2021.).

pružaju podlogu za promišljanje u kontekstu postupanja tijekom obnove.⁴

Potres u ožujku 2020.

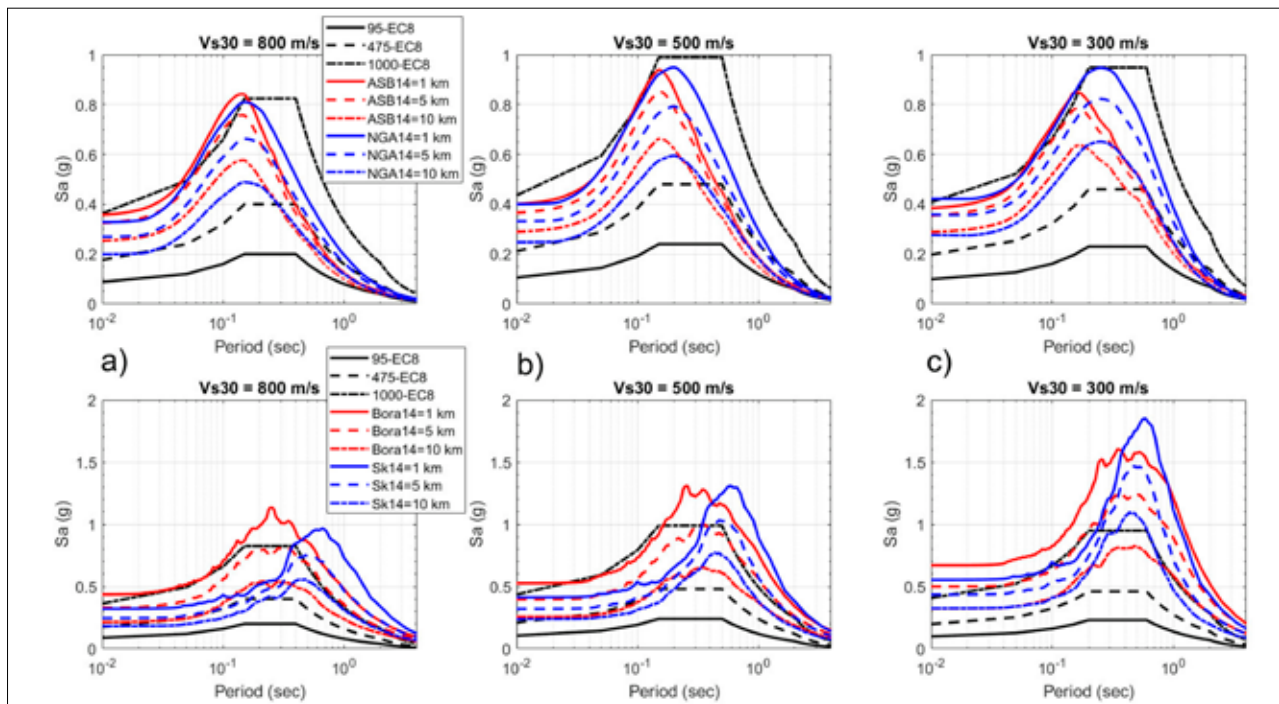
Potres magnitude $M_w=5,4$ koji je Hrvatsku pogodio 22. ožujka 2020. godine najviše se osjetio u sjevernoj Hrvatskoj te u susjednim zemljama, Sloveniji i Bosni i Hercegovini. Epicentar potresa bio je oko 7 km sjeverno od centra Zagreba, u prigradskim naseljima Markuševac i Čučerje, a hipocentar je bio na dubini od oko 10 km, ispod planine

4 Daljnje pojedinosti o seizmološkim aspektima ovih potresa i njihovim utjecajima na izgrađeni okoliš dostupne su u SO, EMILY et al., 2020.; PREVOLNIK, SNJEŽAN et al., 2021.; ATALIĆ, JOSIP et al. 2021.; STEPINAC, MISLAV et al., 2021. za slučaj potresa u ožujku 2020., te u MARKUŠIĆ, SNJEŽANA et al., 2021.; MIRANDA, EDUARDO et al., 2021. za slučaj potresa u prosincu 2020.

Medvednice. S obzirom na karakteristike ovoga potresa epicentrom u blizini središta Zagreba, kretanje tla kakvo je zabilježila postaja smještena u zagrebačkom Uredu za upravljanje u hitnim situacijama u središtu grada pokazuje da je potres imao impulsne karakteristike i kratko trajao (oko 10 s), kao što je vidljivo iz sl. 1. Za to kretanje tla, za koje se pretpostavlja da je zabilježeno na temeljnom tlu tipa C (prema nazivlju Eurokoda 8⁵) utvrđeno je da je vršno ubrzanje tla iznosilo 0,22 g.⁶ Za bolje razumijevanje intenziteta ovoga događaja i njegovih mogućih utjecaja na povijesne građevine u centru Zagreba, važno je usporediti spektar odgovora ovoga događaja sa spektrom odgovora Eurokoda 8 koji se koristi za seizmički proračun na području Zagreba. U tom smislu,

5 EC8-1, 2004.

6 ŠAVOR NOVAK, MARTA et al., 2020.



3 5%-damped elastic response spectra of Eurocode 8 (EC8) for return periods of 95, 475 and 1000 years, compared with the response spectra derived from the ASB14 and NGA14 GMPEs for distances of 1 km, 5 km and 10 km away from the epicentre and for a soil of Type A (a), B (b) and C (c) (adapted from MARKUŠIĆ et al., 2021).

Elastični spektri odgovora za 5-postotno prigušenje iz Eurokoda 8 (EC8) za povratna razdoblja od 95, 475 i 1000 godina, u usporedbi sa spektrima odgovora izvedenima iz ASB14 i NGA14 GMPE za udaljenosti od 1 km, 5 km i 10 km od epicentra i za tlo tipa A (a), B (b) i C (c) (prilagođeno prema MARKUŠIĆ et al., 2021).

BRIEF DESCRIPTION OF RELEVANT CHARACTERISTICS OF THE 2020 EARTHQUAKES

The following sections do not provide detailed accounts of the two earthquakes and their impacts. Instead, certain aspects related with the intensity of these earthquakes are addressed, which provide food for thought in the context of the recovery actions.⁴

The March 2020 earthquake

The magnitude M_w 5.4 earthquake that hit Croatia on March 22, 2020, was mostly felt in northern Croatia, as well as in neighbouring countries such as Slovenia or Bosnia and Herzegovina. The earthquake epicentre was located about 7 km north of the Zagreb downtown area, in the suburb areas of Markuševac and Čučerje, and the hypocentre was at a depth of approximately 10 km, below the Medvednica Mountain. Given the near-field features of this earthquake with respect to downtown Zagreb, the ground motion recorded by the station located at the Zagreb Emergency Management Office in the downtown area exhibits pulselike characteristics and a short duration (approximately 10s), as can be seen from Figure 1. For this ground motion, which is assumed to have

been recorded on a foundation soil of type C (following the Eurocode 8 notation⁵), the peak ground acceleration was found to be 0.22g.⁶ To better understand the intensity of this event and its likely impacts on the historic buildings of downtown Zagreb, it is important to compare the response spectrum of this event with the response spectrum of Eurocode 8 that is used for seismic design in the area of Zagreb. As such, Figure 2 presents the 5%-damped response spectra of the North-South (N-S) and East-West (E-W) components of the recorded ground motion, as well as the Eurocode 8 elastic response spectra for return periods of 95, 225 and 475 years relevant for that area. By analysing the response spectra of the recorded ground motion components, it can be seen that most of the energy content is concentrated in the low period range (0.05s to 0.5s), as typical in near-field ground motions. Furthermore, for periods of vibration lower than 0.2s (where the horizontal plateau of the Eurocode 8 response spectra starts), it can be seen that the intensity of this earthquake is roughly equivalent to that of an event compatible with a return period of 225 years, although for some periods of vibration it also reaches the intensity of the 475-year response spectrum (i.e. the one that would be considered for the seismic design of a new residential building). On the contrary, for periods of vibration between 0.2s and 0.6s (the period range corresponding to the horizontal

4 Further details on the seismological aspects of these earthquakes and their impacts on the built environment can be obtained from SO, EMILY et al., 2020; PREVOLNIK, SNJEŽAN et al., 2021; ATALIĆ, JOSIP et al., 2021; STEPINAC, MISLAV et al., 2021 for the case of the March 2020 earthquake, and from MARKUŠIĆ, SNJEŽANA et al., 2021; MIRANDA, EDUARDO et al., 2021 for the case of the December 2020 earthquake.

5 EC8-1, 2004
6 ŠAVOR NOVAK, MARTA et al., 2020



4 Main façade of the Church of St. Catherine of Alexandria in Zagreb (photo: X. Romão, July 2021)

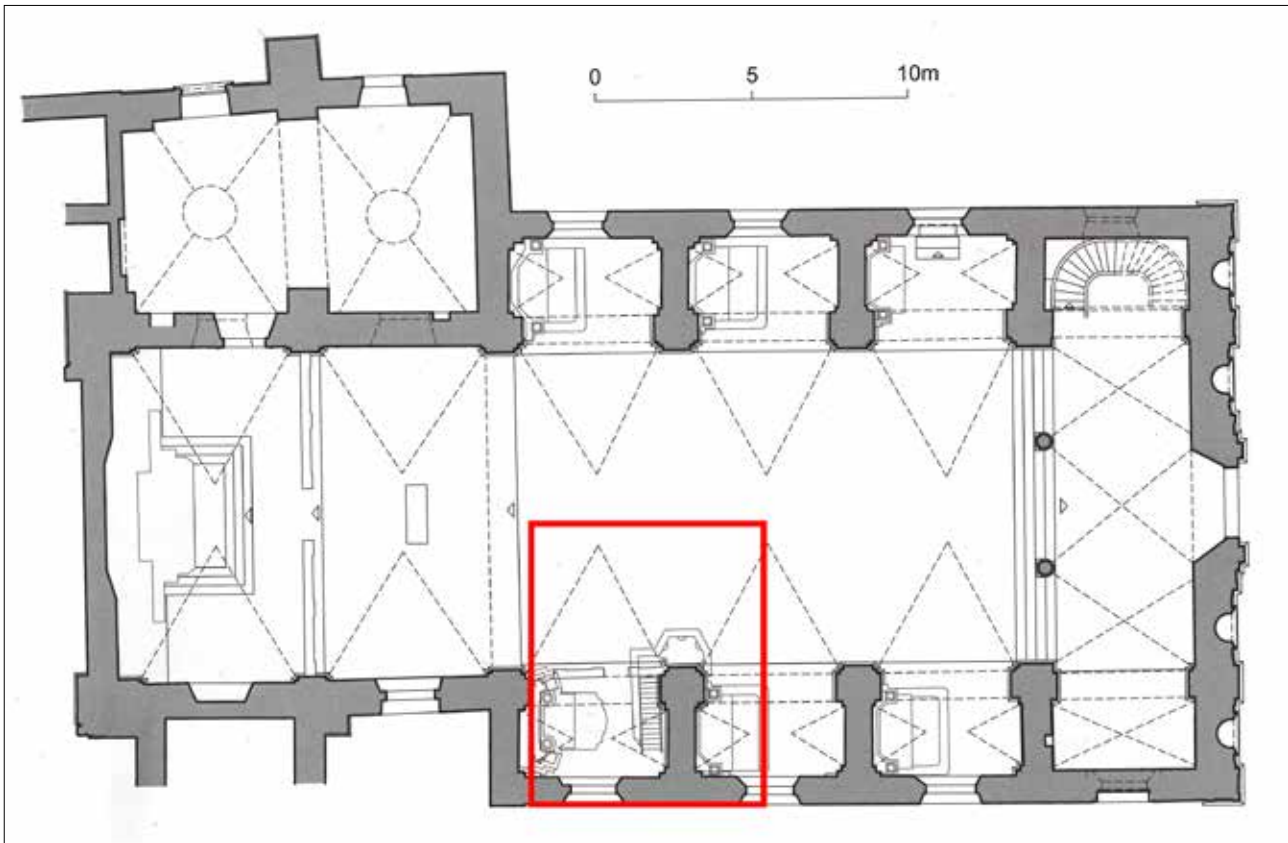
Glavno pročelje crkve Svete Katarine Aleksandrijske u Zagrebu (foto: X. Romão, srpanj 2021.)

sl. 2 prikazuje spektar odgovora za 5-postotno prigušenje za komponente sjever-jug (NS) i istok-zapad (EW) zabilježenog kretanja tla, kao i elastične spektre odgovora Eurokoda 8 za povratna razdoblja od 95, 225 i 475 godina relevantna za to područje. Analizom spektra odgovora zabilježenih komponenti kretanja tla može se vidjeti da je većina sadržaja energije koncentrirana u niskom rasponu perioda (0,05 s do 0,5 s), kao što je tipično za kretanja tla u blizini epicentra potresa. Nadalje, za periode vibracija manje od 0,2 s (gdje počinje horizontalni plato spektra odgovora Eurokoda 8), može se vidjeti da je intenzitet ovog potresa otprilike jednak intenzitetu događaja kompatibilnog s povratnim razdobljem od 225 godina, iako za neke periode vibracija također doseže intenzitet 475-godišnjeg spektra odgovora (tj. onog koji bi se razmatrao za seizmički proračun nove stambene zgrade). Naprotiv, za periode vibracija između 0,2 s i 0,6 s (raspon koji odgovara horizontalnom platou spektra odgovora iz Eurokoda 8), intenzitet ovog potresa može se smatrati bližim

intenzitetu događaja kompatibilnog s povratnim razdobljem od 95 godina, iako se za neke periode vibracija približava intenzitetu spektra odgovora od 225 godina.

Ova je analiza relevantna u kombinaciji s postojećim rezultatima o osnovnom periodu vibracija povijesnih građevina čije su karakteristike slične onima u centru Zagreba. Prema podacima koje su predstavili Atalić et al.⁷ za tipologije reprezentativne za povijesni centar Zagreba, te djelomično prikazane u tablici 1, uočava se da nekoliko tipologija zgrada ima osnovne periode vibracija manje od ili blizu 0,2 s. To znači da je za te zgrade potres iz ožujka 2020. bio događaj za koji se može pretpostaviti da je kompatibilan s povratnim razdobljem od 225 godina. S druge strane, podaci u tablici 1 također prikazuju tipologije zgrada kod kojih su periodi vibracija u temeljima u rasponu od 0,3 do 0,4 s, a za koje je potres iz ožujka 2020. bio događaj s povratnim razdobljem

⁷ ATALIĆ, JOSIP et al., 2021.



5 Floor plan of the Church of St. Catherine of Alexandria, with the identification of the zone where the partial collapse of the vault and the triumphal arch occurred (red line), (adapted from HORVAT-LEVAJ et al., 2011)

Tlocrt crkve Svete Katarine Aleksandrijske uz identifikaciju zone u kojoj je došlo do djelomičnog urušavanja svoda i trijumfalnog luka (crvena linija), (prilagođeno prema HORVAT-LEVAJ et al., 2011.)

plateau of the Eurocode 8 response spectra), the intensity of this earthquake can be considered to be much closer to that of an event compatible with a return period of 95 years, even though for some periods of vibration it approaches the intensity of the 225-year response spectrum.

This analysis is relevant when combined with existing results about the fundamental period of vibration of historic buildings with characteristics similar to those found in downtown Zagreb. According to the data presented by Atalić et al.⁷ for building typologies that are representative of the historic centre of Zagreb, which are partially reproduced in Table 1, it can be seen that several building typologies have fundamental periods of vibration below or close to 0.2s. This means that, for these buildings, the March 2020 earthquake is an event that can be assumed to be compatible with a return period of 225 years. On the other hand, the data in Table 1 also contains building typologies that have fundamental periods of vibration in the range of 0.3-0.4s, for which the March 2020 earthquake is an event with a return period closer to 95 years. To complement these data, Table 2 presents average estimates of the vibration periods of the first three vibration modes (when available) for several

historic buildings in Zagreb.⁸ If the soil conditions can be assumed to still be compatible with the previously referred type C, it can be seen that the earthquake impacts on these buildings are likely to be compatible with those of an event with a return period closer to 95 years.

In light of this analysis, it can be seen that, for a large portion of buildings in the downtown area of Zagreb and near the Zagreb Emergency Management Office, the March 2020 earthquake is likely to have been an event with an intensity similar to that represented by an elastic response spectrum associated with a return period of 95 years. Still, in some cases, this intensity may have been closer to that represented by an elastic response spectrum associated with a return period of 225 years. However, it is impossible to say for sure which buildings underwent a larger intensity event.

The December 2020 earthquake

On December 29, 2020, a magnitude M_w 6.4 earthquake occurred in the Sisak-Moslavina county of Croatia, approximately 47 km south of Zagreb, and was felt also in neighbouring countries such as Slovenia, Bosnia and Herzegovina, Serbia, Hungary, Slovakia and Italy.⁹ The

⁷ ATALIĆ, JOSIP et al., 2021

⁸ BEGOVIĆ, SLAVEN; PEJIĆ, TANJA; VIŠNJEVIĆ, VJERAN, 2012

⁹ MARKUŠIĆ, SNJEŽANA et al., 2021

Tablica 1. Osnovni periodi vibracija uzduž glavnih ortogonalnih pravaca X i Y (Tx i Ty) za različite tipove zgrada nearmirane zidane konstrukcije, uobičajene u povijesnoj cjelini Zagreba (prilagođeno prema ATALIĆ et al., 2021.).

Vrsta funkcije	Pozicija	Katnost	Neto površina (m ²)	Osnovni period vibracija (s)
Stambena	Blok zgrada	5	400	T _x =0,39, T _y =0,31
Obrazovna	Samostojeća zgrada	3	1.250	T _x =0,41, T _y =0,31
Stambena	Blok zgrada	2	120	T _x =0,10, T _y =0,05
Stambena	Blok zgrada	3	170	T _x =0,10, T _y =0,08
Stambena	Zgrade u nizu	3	180	T _x =0,10, T _y =0,08
Stambeno-poslovna	Samostojeća zgrada	5	1100	T _x =0,24, T _y =0,16
Stambeno-poslovna	Samostojeća zgrada	4	900	T _x =0,31, T _y =0,25

Tablica 2. Prosječne procjene perioda vibracija prva tri moda vibracija za glavne ortogonalne pravce nekoliko povijesnih zgrada u Zagrebu (prilagođeno prema BEGOVIĆ et al., 2012.); „n. d.“ odnosi se na nedostupne procjene.

Zgrada	Periodi vibracija (s) - uzdužni smjer			Periodi vibracija (s) - poprečni smjer		
	1. mod	2. mod	3. mod	1. mod	2. mod	3. mod
Zagrebačka katedrala	1,27	1,07	0,92	1,07	0,92	0,74
Hrvatsko narodno kazalište	0,35	0,23	0,15	0,31	0,23	n.d.
Muzej Mimara	0,27	n.d.	n.d.	0,34	n.d.	n.d.
Rektorat Sveučilišta u Zagrebu	0,40	0,30	0,26	0,42	0,23	n.d.
Hrvatski sabor	0,32	0,13		0,33	n.d.	n.d.
Hotel Regent Esplanade	0,44	0,28	0,24	0,43	0,36	0,28
Državni hidrometeorološki zavod (sjeverno krilo)	0,32	0,28	n.d.	0,35	n.d.	n.d.
Državni hidrometeorološki zavod (južno krilo)	0,33	n.d.	n.d.	0,26	n.d.	n.d.
Državni hidrometeorološki zavod (srednje krilo)	0,39	0,29	0,25	0,39	0,29	n.d.

bližim 95 godina. Ti podaci dopunjeni su prikazom u tablici 2 prosječnih procijenjenih perioda vibracija, tj. prva tri moda vibracija (ako su dostupni) za nekoliko povijesnih zgrada u Zagrebu.⁸ Uz pretpostavku da su uvjeti tla i dalje kompatibilni s prethodno navedenim tipom C, može se vidjeti da će učinci potresa na ove zgrade vjerojatno biti kompatibilni s onima događaja s povratnim razdobljem bližim 95 godina.

S obzirom na tu analizu, proizlazi da je za velik dio zgrada u zagrebačkom Donjem gradu i u blizini zagrebačkog Ureda za upravljanje u hitnim situacijama potres iz ožujka 2020.

vjerojatno bio događaj intenziteta sličnog onom prikazanom elastičnim spektrom odgovora povezanim s povratnim razdobljem od 95 godina. Ipak, u nekim je slučajevima taj intenzitet možda bio bliži onom koji predstavlja elastični spektar odgovora povezan s povratnim razdobljem od 225 godina. Međutim, nije moguće sa sigurnošću ustvrditi koje su zgrade bile podvrgnute događaju većeg intenziteta.

Potres u prosincu 2020.

Dana 29. prosinca 2020. potres magnitude M_w 6,4 pogodio je Sisačko-moslavačku županiju u Hrvatskoj, otprilike 47 km južno od Zagreba, a osjetio se i u susjednim zemljama:

⁸ BEGOVIĆ, SLAVEN; PEJIĆ, TANJA; VIŠNJEVIĆ, VJERAN, 2012.

Table 1 – Fundamental periods of vibration along the main X and Y orthogonal directions (Tx and Ty) for different types of unreinforced masonry buildings commonly found in the historic area of Zagreb (adapted from ATALIĆ et al., 2021).

Type of occupancy	Position	Number of stories	Footprint area (m ²)	Fundamental period of vibration (s)
Residential	Block of buildings	5	400	Tx=0.39, Ty=0.31
Educational	Single building	3	1250	Tx=0.41, Ty=0.31
Residential	Block of buildings	2	120	Tx=0.10, Ty=0.05
Residential	Block of buildings	3	170	Tx=0.10, Ty=0.08
Residential	Row of buildings	3	180	Tx=0.10, Ty=0.08
Residential and commercial	Single building	5	1100	Tx=0.24, Ty=0.16
Residential and commercial	Single building	4	900	Tx=0.31, Ty=0.25

Table 2 – Average estimates of the vibration periods of the first three vibration modes for the main orthogonal directions of several historic buildings in Zagreb (adapted from BEGOVIĆ et al., 2012); "n.a." refers to unavailable estimates.

Building	Periods of vibration (s) - longitudinal direction			Periods of vibration (s) - transversal direction		
	1 st mode	2 nd mode	3 rd mode	1 st mode	2 nd mode	3 rd mode
Zagreb Cathedral	1.27	1.07	0.92	1.07	0.92	0.74
Croatian National Theatre	0.35	0.23	0.15	0.31	0.23	n.a.
Mimara Museum	0.27	n.a.	n.a.	0.34	n.a.	n.a.
Rectorate of the University of Zagreb	0.40	0.30	0.26	0.42	0.23	n.a.
Croatian Parliament	0.32	0.13		0.33	n.a.	n.a.
Hotel Regent Esplanade	0.44	0.28	0.24	0.43	0.36	0.28
State Hydrometeorological Institute (north wing)	0.32	0.28	n.a.	0.35	n.a.	n.a.
State Hydrometeorological Institute (south wing)	0.33	n.a.	n.a.	0.26	n.a.	n.a.
State Hydrometeorological Institute (middle wing)	0.39	0.29	0.25	0.39	0.29	n.a.

earthquake epicentre was located about 3 km southwest of the town of Petrinja and 12-15km southwest of the city of Sisak, while the hypocentre was at a depth of approximately 10-11km. Like the March 2020 earthquake, this event can also be considered a near-field earthquake with respect to Petrinja, Glina and Sisak. The duration of the event near the epicentre was approximately 10 s, while in Zagreb the duration that was felt increased to about 20-30 s due to spreading effects through different layers of soil¹⁰ and the peak ground acceleration was estimated to be 0.5g in areas

at a distance of approximately 5 km from the epicentre, 0.2g at a distance of approximately 20–30 km and 0.1g at a distance of approximately 50 km.¹¹ Close to the epicentre, the equivalent peak ground acceleration on rock was estimated to be approximately 0.3g which is close to twice the seismic design level acceleration for that area (0.16g) and highlights the significance of this earthquake within the known historical seismicity of the region.

Although there were no earthquake recording stations near the epicentre area to record the event, a series of studies

¹⁰ RADNIĆ, JURA et al., 2021

¹¹ MARKUŠIĆ, SNJEŽANA et al., 2021



6 General view of the external damage of the church, where there is no evidence of masonry crushing at the anchorage zones of the tie rods (photo: X. Romão, July 2021)

Opći pogled na vanjsko oštećenje crkve, gdje nema tragova drobljenja zidane konstrukcije na mjestima sidrenja zatega (foto: X. Romão, srpanj 2021.)

Sloveniji, Bosni i Hercegovini, Srbiji, Mađarskoj, Slovačkoj i Italiji.⁹ Epicentar potresa bio je oko 3 km jugozapadno od grada Petrinje i 12-15 km jugozapadno od grada Siska, dok je hipocentar bio na dubini od otprilike 10-11 km. Poput potresa u ožujku 2020., i ovaj se događaj može smatrati potresom u kojem je epicentar u blizini gradova, odnosno Petrinje, Gline i Siska. Trajanje događaja procijenjeno je na 10 s uz epicentar, dok se osjećaj trajanja na području Zagreba povećao na 20-30 s zbog učinaka širenja kroz različite slojeva tla,¹⁰ a vršno ubrzanje tla procijenjeno je na 0,5 g u područjima na udaljenosti od približno 5 km od epicentra, 0,2 g na udaljenosti od približno 20-30 km i 0,1 g na udaljenosti od približno 50 km.¹¹ U blizini epicentra je ekvivalentno vršno ubrzanje tla na stijeni procijenjeno na približno 0,3 g,, što je gotovo dvostruko više od projektiranoga seizmičkog ubrzanja za to područje (0,16 g) te naglašava važnost koju ovaj potres ima unutar poznate povijesne seizmičnosti ove regije.

Iako u blizini područja epicentra nije bilo postaja za bilježenje potresa, provedeno je niz istraživanja na temelju podataka koje su zabilježile postaje u blizini Zagreba.¹² Ti su zapisi zatim objedinjeni u različitim atenuacijskim relacijama gibanja tla (GMPE), za koje je utvrđeno da su prikladne za lokalni kontekst toga područja, kako bi se procijenio

vjerojatni spektar odgovora ovoga događaja za 5-postotno prigušenje u blizini epicentralnog područja za različite uvjete tla.¹³ Na sl. 3 prikazan je procijenjeni spektar odgovora potresa uz pretpostavku 5-postotnog prigušenja za tipove tla A, B i C (prema nazivlju Eurokoda 8), uzimajući u obzir dva različita GMPE-a i za lokacije udaljene 1, 5 i 10 km od epicentra. Uz navedeno, prikazani su i odgovarajući elastični spektri odgovora iz Eurokoda 8 za to područje i za povratna razdoblja od 95, 475 i 1000 godina.

U slučaju potresa u ožujku 2020., prikazani spektri odgovora (sl. 3) mogu pružiti važne uvide u intenzitet potresa koji su podnijele povijesne građevine na području oko epicentra (Petrinja je od epicentra udaljena manje od 5 km, Glina i Sisak su oko 12-15 km od epicentra, a Pokupsko je na udaljenosti od otprilike 20 km od epicentra). Analizom ovih spektara odgovora uviđa se da je za udaljenosti od epicentra do 5 km (kao u slučaju Petrinje) i za zgrade s osnovnim periodom vibracija manjim od 0,15 s, očekivani intenzitet potresa blizak događaju s povratnim razdobljem od 1.000 godina, bez obzira na vrstu tla. Za zgrade s osnovnim periodom vibracija između 0,15 s i 0,4-0,6 s (ovisno o vrsti tla), očekivani intenzitet potresa je između intenziteta događaja s povratnim razdobljem od 1000 godina i intenziteta događaja s povratnim razdobljem od 475 godina (tj. onoga koji bi se uzimao u obzir kod seizmičkog proračuna nove stambene zgrade). Za zgrade s osnovnim periodom

9 MARKUŠIĆ, SNJEŽANA et al., 2021.

10 RADNIĆ, JURE et al., 2021.

11 MARKUŠIĆ, SNJEŽANA et al., 2021.

12 PREVOLNIK, SNJEŽAN, 2021.

13 MARKUŠIĆ, SNJEŽANA et al., 2021.



7 Anchorage points of one of the tie rods of the triumphal arch seen from the outside a) view of the left lateral wall where masonry crushing can be seen and, b) view of the right lateral wall where there are no signs of masonry crushing (photo: X. Romão, July 2021)

Točke sidrenja jedne od zatega trijumfalnog luka u pogledu izvana: a) pogled na lijevi bočni zid gdje je vidljivo drobljenje zidane konstrukcije i, b) pogled na desni bočni zid gdje nema znakova drobljenja zidane konstrukcije (foto: X. Romão, srpanj 2021.)

have been carried out based on data recorded by stations near Zagreb.¹² These records were then combined with different ground motion prediction equations (GMPEs) found to be adequate for the local context of that area to estimate the likely 5%-damped response spectrum of this event near the epicentral area for different soil conditions.¹³ Figure 3 presents the estimated 5%-damped response spectra of the earthquake for soil types A, B and C (following the Eurocode 8 notation) considering two different GMPEs and for locations that are 1, 5 and 10 km away from the epicentre. In addition, Figure 3 also presents the corresponding Eurocode 8 elastic response spectra for that area and for return periods of 95, 475 and 1000 years.

As for the March 2020 earthquake, the response spectra shown in Figure 3 can provide important insights regarding the earthquake intensity sustained by the historic buildings of the area surrounding the epicentre (Petrinja is closer than 5 km from the epicentre, Glina and Sisak are approximately 12-15 km away from the epicentre, and Pokupsko is approximately 20 km away from the epicentre). By analysing these response spectra, it can be seen that, for epicentral distances up to 5 km (as in the case of Petrinja) and for buildings with a fundamental period of vibration lower than 0.15s, the expected intensity of the earthquake is close to that of an event with a return period of 1000 years, irrespective of the soil type. For buildings with a fundamental period

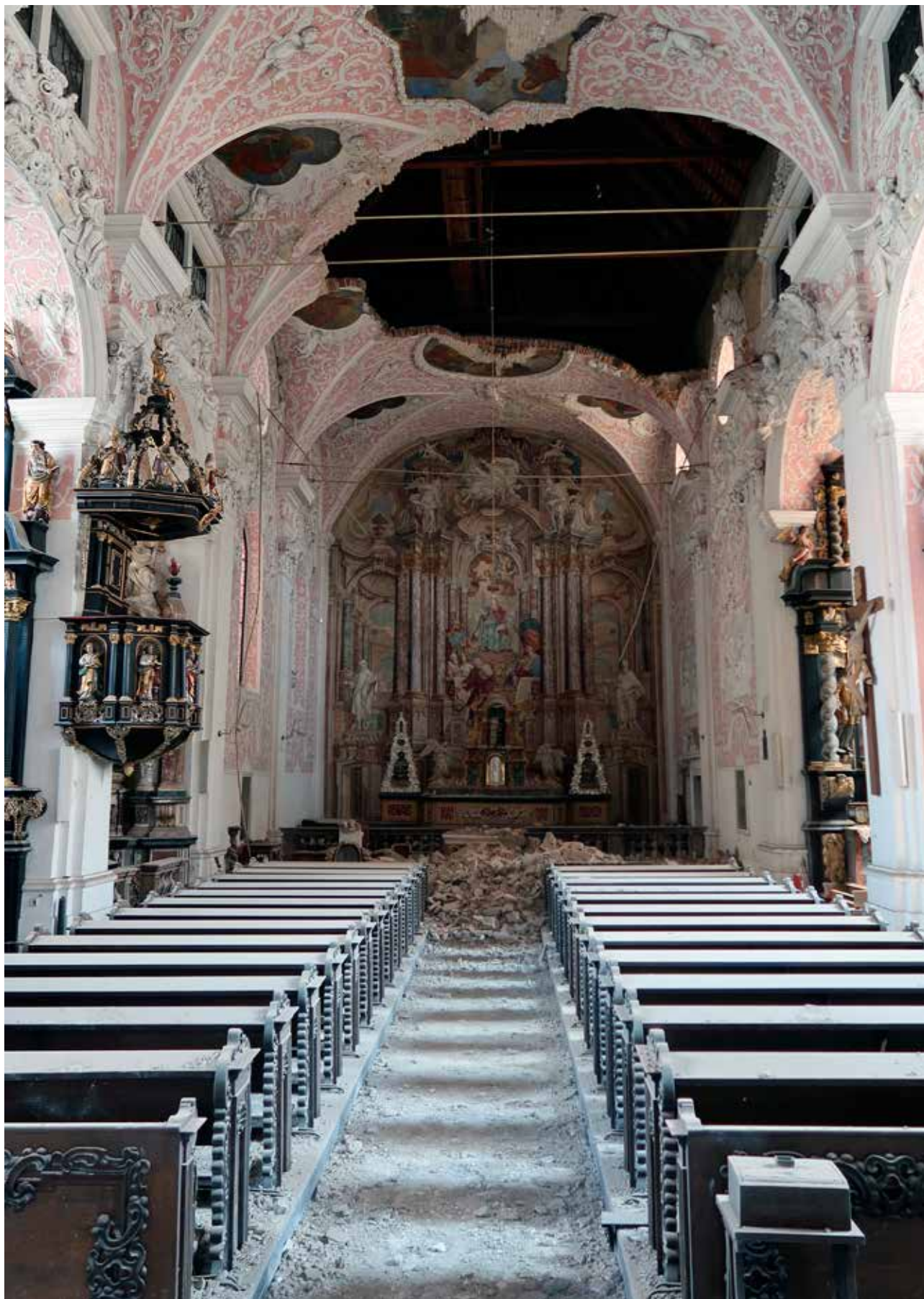
of vibration between 0.15s and 0.4-0.6s (depending on the soil type), the expected intensity of the earthquake is between that of an event with a return period of 1000 years and that of an event with a return period of 475 years (i.e., the one that would be considered for the seismic design of a new residential building). For buildings with a fundamental period of vibration higher than 0.4-0.6s (depending on the soil type), the expected intensity of the earthquake is close to that of an event with a return period of 475 years.

For areas at an epicentral distance of 10 km that have a foundation soil that is of type A or B and for buildings with a fundamental period of vibration up to 0.3-0.4s, the expected intensity of the earthquake is mostly close to that of an event with a return period of 475 years. For buildings with a higher fundamental period of vibration, the expected intensity of the earthquake is between that of an event with a return period of 475 years and that of an event with a return period of 95 years (probably that of an event with a return period of 225 years). However, for areas where the foundation soil is of type C (as in the areas close to Glina and Sisak)¹⁴ and for buildings with a fundamental period of vibration up to 0.5-0.6s, the expected intensity of the earthquake is significantly higher than that of an event with a return period of 475 years. For buildings with a higher fundamental period of vibration, the expected intensity of the earthquake is that of an event with a return period of 475 years.

¹² PREVOLNIK, SNJEŽAN, 2021

¹³ MARKUŠIĆ, SNJEŽANA et al., 2021

¹⁴ MARKUŠIĆ, SNJEŽANA et al., 2021



8 General view of the collapsed areas from the inside of the church (photo: X. Romão, July 2021)
Opći pogled na urušene zone unutar crkve (foto: X. Romão, srpanj 2021.)



9 Detail of the failure of the triumphal arch tie rod (photo: X. Romão, July 2021)

Detalj loma zatege trijumfalnog luka (foto: X. Romão, srpanj 2021.)



10 Longitudinal cracking along the vault crown line (photo: X. Romão, July 2021)

Uzdužna pukotina uzduž linije tjemena svoda (foto: X. Romão, srpanj 2021.)



11 Detachment of finishing plasters of the nave vault (photo: X. Romão, July 2021)

Odvajanje završnih slojeva žbuke svoda središnjeg broda (foto: X. Romão, srpanj 2021.)



12 Possible constructive joint running along the upper choir arch (photo: X. Romão, July 2021)

Moguć konstrukcijski spoj uzduž luka kora (foto: X. Romão, srpanj 2021.)



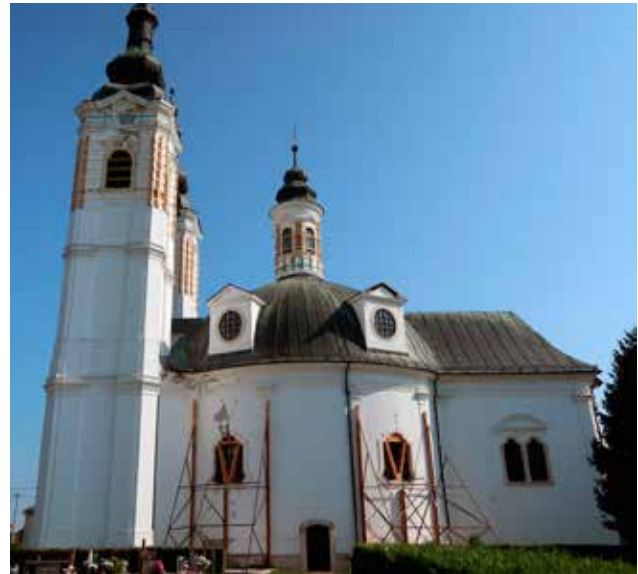
13 Sela, main façade of the Church of St. Mary Magdalene (photo: X. Romão, July 2021)

Sela, glavno pročelje crkve sv. Marije Magdalene (foto: X. Romão, srpanj 2021.)

vibracija većim od 0,4 do 0,6 s (ovisno o vrsti tla), očekivani intenzitet potresa blizak je intenzitetu događaja s povratnim razdobljem od 475 godina.

Za područja na udaljenosti od 10 km od epicentra koja imaju temeljno tlo tipa A ili B i za zgrade s osnovnim periodom vibracija do 0,3 do 0,4 s, očekivani intenzitet potresa uglavnom je blizu intenziteta potresa događaja s povratnim razdobljem od 475 godina. Za zgrade s većim osnovnim periodom vibracija očekivani intenzitet potresa je između intenziteta događaja s povratnim razdobljem od 475 godina i događaja s povratnim razdobljem od 95 godina (vjerojatno događaja s povratnim razdobljem od 225 godina). Međutim, za područja gdje je temeljno tlo tipa C (kao u područjima u blizini Gline i Siska)¹⁴ i za zgrade s osnovnim periodom vibracija do 0,5 do 0,6 s, očekivani intenzitet potresa znatno je veći od događaja s povratnim razdobljem od 475 godina. Za zgrade s većim osnovnim periodom vibracija očekivani intenzitet potresa je blizak intenzitetu događaja s povratnim razdobljem od 475 godina.

Temeljem ove analize proizlazi da je za grad Petrinju potres u prosincu 2020. vjerojatno bio događaj s intenzitetom znatno većim od onog predstavljenog elastičnim spektrom odgovora povezanim s povratnim razdobljem od 475 godina. S druge strane, za zgrade na području Gline i Siska potres



14 Lateral elevation view of the nave, showing the dome and the skylight windows (photo: X. Romão, July 2021)

Pogled na bočnu elevaciju zida središnjeg broda, na kojem su prikazani kupola i prozorske kućice svoda (foto: X. Romão, srpanj 2021.)

iz prosinca 2020. vjerojatno je bio događaj intenziteta bliskog događaju s povratnim razdobljem od 475 godina, dok su zgrade na području Pokupskog pretrpjele potres manjeg intenziteta, vjerojatno bližeg događaju s povratnim razdobljem od 225 godina.

OPIS I ANALIZA DVIJU GRAĐEVINA KULTURNE BAŠTINE OŠTEĆENIH U POTRESIMA

Radi ilustracije utjecaja ovih dvaju potresa na građevine kulturne baštine u pogođenim područjima, sljedeći odlomci donose kratke opise i analize crkve Svete Katarine Aleksandrijske u Zagrebu, koja je oštećena u potresu u ožujku 2020., te crkve Svete Marije Magdalene u Selima, koja je oštećena u potresu u prosincu 2020. Ovi nalazi temelje se na opažanjima tijekom izvida na terenu na potresima pogođenim područjima, a koji su obavljani u srpnju 2021.

Crkva svete Katarine Aleksandrijske

Crkva Svete Katarine Aleksandrijske (sl. 4) nalazi se na Trgu Svete Katarine u Zagrebu. Prema informacijama koje je Ministarstvo podijelilo tijekom izvidnih posjeta, crkva je izgrađena između 1620. i 1632. godine na mjestu nekadašnje dominikanske crkve iz 15. stoljeća. Prvotni projekt glavnog pročelja uključivao je dva niska zvonika koji su uklonjeni 1874.¹⁵ U 17. stoljeću crkva je više puta morala biti obnavljana zbog požara¹⁶, a 1881. godine izvršena je još jedna obnova nakon potresa 1880. godine.¹⁷

14 MARKUŠIĆ, SNJEŽANA et al., 2021.

15 HORVAT-LEVAJ, KATARINA; REPANIĆ-BRAUN, MIRJANA, 2021.

16 DOBRONIĆ, LELJA, 2000.

17 HORVAT-LEVAJ, KATARINA, 2008.



15 Cracking in the main façade (photo: X. Romão, July 2021)
Pukotine na glavnom pročelju (foto: X. Romão, srpanj 2021.)



16 Detail of the main entrance (photo: X. Romão, July 2021)
Detalj glavnog ulaza (foto: X. Romão, srpanj 2021.)

In light of this analysis, it can be seen that, for the town of Petrinja, the December 2020 earthquake is likely to have been an event with an intensity significantly higher than the one represented by an elastic response spectrum associated with a return period of 475 years. On the other hand, for buildings in the areas of Glina and Sisak, the December 2020 earthquake is likely to have been an event with an intensity close to that of an event with a return period of 475 years, while buildings in the area of Pokupsko sustained a lower intensity earthquake, probably closer to that of an event with a return period of 225 years.

DESCRIPTION AND ANALYSIS OF TWO CULTURAL HERITAGE BUILDINGS DAMAGED BY THE EARTHQUAKES

To illustrate the impacts of these two earthquakes on cultural heritage buildings in the affected areas, the following sections present a brief description and analysis of the Church of St. Catherine of Alexandria in Zagreb damaged by the March 2020 earthquake, and the Church of St. Mary Magdalene in Sela damaged by the December 2020 earthquake. These findings are based on observations made during a reconnaissance visit to the areas affected by the earthquakes that was carried out in July 2021.

Church of St. Catherine of Alexandria

The Church of St. Catherine of Alexandria (Fig. 4) is located at the St. Catherine square in Zagreb. According to information provided by the Ministry during the reconnaissance visit, the church was built between 1620 and 1632 where a former Dominican church from the 15th century was located. The original design of the main façade included two low bell towers that were removed in 1874.¹⁵ In the 17th century, the church had to be renovated several times due to fires¹⁶, and in 1881, a new renovation was carried out following the 1880 earthquake.¹⁷

During the reconnaissance visit, it was possible to observe the church structure both from the outside and the inside. Still, it was not possible to have access to the roof structure in order to analyse it more closely. The church is regular in plan, comprising a main altar, a nave and an upper choir. The church has three lateral chapels on each side of the nave, separated by masonry septa that provide lateral bracing to the structure (Fig. 5). The load-bearing structure consists of solid brick walls that support a vaulted ceiling also in brick masonry. Transversally to the nave, there are sets of two metallic tie rods along the alignment of the structural septa that divide the lateral chapels at the

¹⁵ HORVAT-LEVAJ, KATARINA; REPANIĆ-BRAUN, MIRJANA, 2021

¹⁶ DOBRONIĆ, LELJA, 2000

¹⁷ HORVAT-LEVAJ, KATARINA, 2008

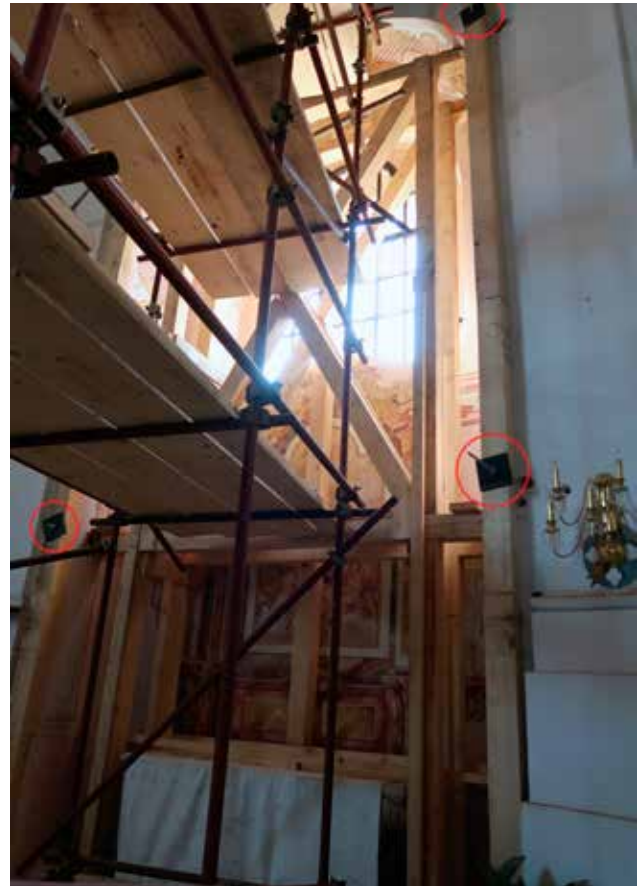


17 External shoring of nave walls in the area of the lateral chapels (photo: X. Romão, July 2021)

Vanjsko podupiranje zidova središnjeg broda u zoni bočnih kapela (foto: X. Romão, srpanj 2021.)

Tijekom izvida na terenu bilo je moguće promatrati konstrukciju crkve i izvana i iznutra. Ipak, nije bilo moguće pristupiti krovnoj konstrukciji i poblizje ju analizirati. Crkva je pravokutnog tlocrta, sastoji se od glavnog oltara, središnjeg broda i kora. Crkva ima tri bočne kapele sa svake strane središnjeg broda, odvojene zidanim pregradama koje bočno podupiru konstrukciju (sl. 5). Nosiva konstrukcija sastoji se od masivnih zidova od opeke koji nose svodeni strop, također zidan opekom. Poprečno na središnji brod su u razini imposta svoda središnjeg broda postavljene po dvije metalne zatege u liniji konstruktivnih pregrada koje dijele bočne kapele. Osim tih zatega, još jedna metalna zatega (koja se činila starijom) primijećena je uzduž kora i na višoj razini. Točke sidrenja nekih od ovih zatega nisu vidljive izvana, konkretno je riječ o sidrenju zatega uzduž kora i jedne od dvije postojeće zatega uzduž trijumfalnog luka.

Oštećenja crkve, koja su se mogla uočiti izvana, nisu bila znatnije izražena. Na pročelju nije bilo bitnih oštećenja, dok su na bočnim nosivim zidovima bile vidljive manje okomite pukotine. Promatranje točaka sidrenja zatega s vanjske strane crkve pokazalo je da ni na jednoj zategi uzduž bočnih zidova središnjeg broda nema tragova drobljenja sidrišta. To znači da je konstrukcija mogla podnijeti pomake uzrokovane potresom



18 Detail of the internal shoring of the lateral chapels and anchorage connections to the exterior (photo: X. Romão, July 2021)

Detalj unutarnjeg podupiranja bočnih kapela i spojeva sidrišta prema van (foto: X. Romão, srpanj 2021.)

u poprečnom smjeru (sl. 6). Međutim, jedina od zatega uzduž trijumfalnog luka vidljiva izvana pokazivala je znakove drobljenja na točki sidrenja koja se nalazi na lijevom bočnom zidu (sl. 7). Naposljetku, promatranje krova s vanjske strane omogućilo je zaključak da bi trebao biti u dobrom stanju jer nisu uočeni dokazi ispupčenja ili nedostajućih crijepova.

Oštećenja uočena u unutrašnjosti crkve puno su veća od onih uočanih izvana, i to zbog djelomičnog urušavanja svoda u zoni svoda trijumfalnog luka i gotovo potpunog urušavanja samog trijumfalnog luka (sl. 8) – zona u kojoj je došlo do djelomičnog urušavanja svoda središnjeg broda označena je crvenom bojom na sl. 5. Iznutra su na trijumfalnom luku također bile vidljive dvije zatega te je jedna od njih (vidljiva izvana) pukla u blizini svoje stezne naprave koja se nalazi između imposta luka (sl. 9). Uz to su na svodu uočene i pukotine na nekoliko mjesta, točnije uzdužne pukotine uzduž tjemena svoda (sl. 10), kao i općenita odvojenost dijelova oslikanog sloja svoda središnjeg broda (sl. 11). Uočene poprečne pukotine na svodu uzduž luka kora upućuju na prethodno postojanje konstrukcijskog spoja koje je moglo nastati u prošlosti tijekom radova na rekonstrukciji ili obnove građevine (sl. 12). Naposljetku, kroz urušeni dio svoda bilo je moguće vidjeti drvenu konstrukciju krovništa, no nije bilo moguće utvrditi nikakva oštećenja na istoj.



19 Missing parts of a mural painting in the lateral altars (photo: X. Romão, July 2021)

Nedostajući dijelovi zidnog oslikanja u bočnim oltarima (foto: X. Romão, srpanj 2021.)



20 Vault shoring in the central zone of the dome showing missing parts of the finishings (photo: X. Romão, July 2021)

Podupiranje svoda u središnjoj zoni kupole na kojoj nedostaju dijelovi završnih slojeva (foto: X. Romão, srpanj 2021.)

level of the impost of the nave vault. Aside from these tie rods, another metallic tie rod (that seemed older) was also seen along the alignment of the upper choir and at a higher level. The anchoring point of some of these tie rods is not visible from the outside, namely that of the tie rod along the alignment of the upper choir and of one of the two existing tie rods along the triumphal arch.

The damage to the church that could be observed from the outside was not very expressive. The main façade did not present relevant damage while the lateral load-bearing walls exhibited light vertical cracking. The observation of the anchoring points of the tie rods from the outside of the church showed that none of the tie rods along the lateral walls of the nave exhibited signs of anchorage crushing. This means that the structure was able to accommodate the displacements imposed by the earthquake along the transversal direction (Fig. 6). However, the only tie rod visible from the outside along the alignment of the triumphal arch showed signs of anchorage crushing at the anchoring point located on the left lateral wall (Fig. 7). Finally, the observation of the roof from the exterior allowed concluding that it should be in a good condition since no evidence of bulging or missing tiles was seen.

The damage observed on the interior of the church is much more severe than the one observed from the outside due to the partial collapse of the vault in the triumphal arch area and the almost full collapse of the actual triumphal arch (Fig. 8) – the zone where the partial collapse of the nave vault occurred is also identified in red in Figure 5. From the inside, it was also possible to see that the triumphal arch had two tie-rods and that one of them (the one visible from the outside) broke near its tightening device located between the arch impost (Fig. 9). Additionally, cracking was also observed in several locations of the vault, namely longitudinal cracks along the vault crown (Fig. 10), as well as the generalized detachment of parts of the painted finishing of the nave vault (Fig. 11). The observation of transversal cracking of the vault along the upper choir arch suggests the previous existence of a constructive joint that might have been created by possible reconstruction works or an expansion of the building in the past (Fig. 12). Finally, it was possible to see the wooden truss structure of the roof through the collapsed area of the vault, but no damage was able to be identified.



21 a b Opening of joints between the vault and the external walls of the skylight windows (photo: X. Romão, July 2021)

Otvaranje spojeva između svoda i vanjskih zidova prozorskih kućica (foto: X. Romão, srpanj 2021.)

Crkva Svete Marije Magdalene u Selima

Crkva Svete Marije Magdalene nalazi se u Selima u Sisačko-moslavačkoj županiji. Građena je između 18. i 19. stoljeća te ima iznimnu arhitektonsku vrijednost. Crkvu flankiraju dva zvonika (sl. 13), a njezin je tlocrt eliptične konfiguracije nadsvođene kupolom (sl. 14). Prema onome što se moglo uočiti, i nosivi zidovi i svodovi su zidani opekom. Prema lokalnim informacijama, krovna konstrukcija je drvena.

Tijekom izvida na terenu uočene su pukotine na pročelju i bočnim zidovima središnjeg broda, posebice u zonama otvora koji su trenutačno poduprti iznutra i izvana (sl. 15-18). U unutrašnjosti te zone odgovaraju bočnim kapelama nadsvođenima lukovima na kojima su utvrđena teška oštećenja i dijelovi zidnog oslika koji su otpali (sl. 19). Iako pukotina svoda središnjeg broda nije pretjerano velika, konstrukcija je poduprta u zoni kupole koja je, prema lokalno dobivenim informacijama, imala pukotine u zoni tambura (sl. 20).

Uočeno je i otvaranje spojeva između zona umetanja prozorskih kućica kupole i njima pripadajućih zidova (sl. 21). Činilo se da na svodu i u zoni prozorskih kućica kupole postoji blaga deformacija. Uz to, utvrđena su relevantna puknuća i nedostajući dijelovi završnih slojeva zidova i svoda središnjeg broda, kao i u zoni kora koja se nalazi između dva zvonika, a nose ju plitki lukovi (sl. 22, 23). Na tornjevima su uočene pukotine omeđene na njihovoj gornjoj razini (sl. 24). Zbog predostrožnosti, kupola je također osigurana izvana. Iako su pukotine primijećene i u glavnoj kapeli, ona nije znatno oštećena (sl. 25).

Općenito, uočena oštećenja upućuju na nedostatak horizontalnog omeđenja oko perimetra cijele konstrukcije na vrhu zidova, što je u skladu s uočenim pukotinama iznad otvora i deformacijama plitkih lukova u zoni gornjeg kora.



22 Shoring of the arch supporting the upper-choir, (photo: X. Romão, July 2021)

Podupiranje luka koji nosi kor (foto: X. Romão, srpanj 2021.)

Church of St Mary Magdalene in Sela

The Church of St Mary Magdalene is located in Sela, in the Sisak-Moslavina county. It was built between the 18th and 19th century and has an exceptional architectural value. The church is flanked by two bell-towers (Fig. 13) and its in-plan layout has an elliptical configuration topped by a dome (Fig. 14). From what could be observed, both the load-bearing walls and the vaults are made of brick masonry. According to local information, the roof structure is made of timber.

During the reconnaissance visit, cracking in the façade and lateral walls of the nave was observed, particularly in the zones of openings presently shored internally and externally (Fig. 15-18). Internally, these zones correspond to the lateral chapels topped by arches that exhibited heavy damage and parts of the mural painting that had fallen (Fig. 19). Although the cracking of the nave vault is not very significant, the structure was shored in the area of the dome, which according to local information, exhibited cracking in the drum zone (Fig. 20).

The opening of joints between the insertion zones of the skylight windows of the dome and the walls of the protruding body of those windows towards the exterior was also observed (Fig. 21). In the vault and in the zone of the skylight windows there seemed to be a slight deformation. Additionally, relevant cracking and missing parts of the finishings of the nave walls and vault was also found, as well as in the upper-choir zone located between the two bell-towers and supported by shallow arches (Fig. 22, 23). The towers exhibited cracking and were confined at their upper level (Fig. 24). By precaution, the dome was also externally confined. Although cracking was also observed in the main chapel, it was not significantly damaged (Fig. 25).

Overall, the damage that was observed suggests a lack of horizontal confinement around the perimeter of the whole structure at the top of the walls, which is consistent with the cracks observed above the openings and the deformation of the shallow arches in the upper-choir zone.

RECOMMENDATIONS AND SUGGESTIONS FOR INTERVENTION STRATEGIES

Based on the levels of earthquake damage seen across the cultural heritage buildings that were surveyed during the reconnaissance visit, a series of possible structural intervention strategies are suggested and described (Table 3). These general strategies are not targeting any cultural heritage building in particular, but can be adapted to the needs of specific cases. Overall, these strategies aim at improving the global behaviour of cultural heritage buildings under earthquake loading by enhancing the global confinement and bracing of the structure and improving the connection between the vertical and horizontal structural elements.



23 Shoring of the arch above the upper-choir which supports the nave vault (photo: X. Romão, July 2021)

Podupiranje luka iznad kora koji nosi svod središnjeg broda (foto: X. Romão, srpanj 2021.)

Based on these general strategies and on the specific damage that was observed in the Church of St. Catherine of Alexandria in Zagreb, the following actions are suggested for its repair and rehabilitation:

Repositioning/replacement of the triumphal arch tie rods ensuring they are adequately anchored to the external face of the nave longitudinal walls.

Strengthening of the façade connection to the lateral walls at the upper choir and the roof levels (see strategy I1 in Table 3).

Controlled demolition of unstable zones of the ceiling vault and subsequent reconstruction by ensuring their continuity with the existing vault structure using adequate fastening elements and mortar injections, possibly complemented with a reinforced plaster as described in strategy I5 (see Table 3). In the reconstructed zone of the vault, it must be ensured that the imposts are well connected to the vertical loadbearing structure.

The roof structure should be inspected as soon as safety conditions allow it to determine if further actions are necessary.

Tablica 3. Moguće opće strategije konstrukcijskih zahvata

Zahvat	Opis
11	Koristiti drvene podove i horizontalno položene drvene elemente prisutne u konstrukciji za izradu odgovarajućih dijafragmi koje će omogućiti omeđivanje i povezivanje cijelog sustava zidanih zidova. To se može postići dodatnim horizontalno položenim čeličnim elementima (npr. čelične trake, L-profil ili U-profil), ortogonalno i dijagonalno položenim u odnosu na postojeće drvene elemente (npr. podne grede) i njihovim pričvršćivanjem na iste, u svrhu izvedbe mješovitih vodoravnih rešetki. Takve rešetke trebaju biti povezane sa susjednim zidovima koristeći čelične grede (npr. L-profila ili U-profila ili čeličnih profila s ukrucenjima), koje su na jednakim razmacima usidrene uzduž oboda zidova koristeći odgovarajuće čelične spojnice, što bi u idealnom slučaju trebale biti izvedene preko čitave (ili gotovo čitave) debljine zida.
12	Poboljšati spojeve kod sudara zidova (npr. pročelja i poprečnih zidova) umetanjem čeličnih profila u kutove (po mogućnosti obostrano na zidovima), pričvršćenih za zidove čeličnim šipkama izvedenima kroz čitavu debljinu zida. U nekim slučajevima ti profili mogu biti skriveni debljinom postojeće obložne žbuke. U situaciji u kojoj se koristi strategija I1, vertikalni profili mogu se spojiti (npr. zavariti ili pričvrstiti vijcima) na susjedne horizontalno položene čelične vezne grede. Sve čelične elemente potrebno je zaštititi od korozije. Alternativno, čelični spojnici tipa Cintec ¹ (ili njima ekvivalentni) mogu se koristiti za spojeve sudara zidova.
13	U situacijama kada je obložna žbuka uklonjena sa zidova (ili se očekuje njezino uklanjanje), zidana konstrukcija može se ojačati upotrebom armirane žbuke izrađene od morta armiranog tekstilom (TRM), upotrebom mreže od staklenih, bazaltnih ili ugljičnih vlakana pričvršćene na zid spojnica (npr. armaturnim šipkama ili vijcima od nehrđajućeg čelika) i prekrivene prirodnim hidrauličnim vapnom (NHL 5). To je načelo nalik onom koji se koristi kod izrade armirane betonske obloge (tj. torkretiranja), ali korištenjem materijala koji su kompatibilniji s postojećom zidanom konstrukcijom u vidu čvrstoće, krutosti i kemijskog ponašanja. Ako se koristi istovremeno sa strategijama I1 i I2, ova strategija dovodi do ojačane zidane konstrukcije za koju se očekuje da će biti duktilnija i disipativnija pod djelovanjem potresa, što omogućava uzimanje u obzir niže razine seizmičkog zahtjeva u smislu čvrstoće.
14	Ako sustav preuzimanja bočnih sila nije dovoljan i strategija I3 se ne može provesti, novi sustavi bočnih čeličnih podupora (okviri s dijagonalama) mogu se usvojiti kao reverzibilna alternativa korištenju torkretiranog armiranog betona (tj. mlaznog betona) na postojećoj zidanoj konstrukciji. Ovi novi sustavi podupora mogu se postaviti gdje god je potrebna krutost i/ili čvrstoća. U arhitektonskom smislu, njihova se vidljivost može pretpostaviti kao novi i drugačiji sustav konstrukcije ili se mogu pričvrstiti za postojeće zidove zidane konstrukcije kako bi se smanjila njihova vizualna istaknutost. U svakom slučaju, ovu strategiju treba usvojiti zajedno sa strategijom I1 kako bi se horizontalnim dijafragmama osigurao odgovarajući spoj s postojećim zidovima zidane konstrukcije.
15	Na svodovima bi u zonama pukotina trebala biti izvedena mehanička učvršćenja i injektiran mort (tj. zatvaranje pukotina). Uz to, potpuno pojačanje vanjske linije (ekstradosa) svoda može se izvesti upotrebom armirane obložne žbuke izvedene od TRM-a, upotrebom mreže od staklenih, bazaltnih ili ugljičnih vlakana spojene na zidanoj konstrukciji svoda pomoću šipki ili vijaka od nehrđajućeg čelika te prekrivene prirodnim hidrauličnim vapnom (NHL 5)

PREPORUKE I PRIJEDLOZI ZA STRATEGIJE ZAHVATA

Na temelju razina oštećenja od potresa uočenih na građevinama kulturne baštine ispitanim tijekom izvida na terenu, predlaže se i opisuje niz mogućih strategija konstrukcijskih zahvata (tablica 3). Te opće strategije nisu usmjerene na konkretne građevine kulturne baštine, ali se mogu prilagoditi potrebama specifičnih slučajeva. Općenito, cilj tih strategija je poboljšati općenito ponašanje građevina kulturne baštine pod potresnim opterećenjem povećanjem globalnog omeđenja i podupiranjem

konstrukcije te poboljšanjem veza između vertikalnih i horizontalnih konstrukcijskih elemenata.

Na temelju ovih općih strategija i konkretnih oštećenja koja su uočena u crkvi Svete Katarine Aleksandrijske u Zagrebu, predlažu se sljedeći zahvati za njezin popravak i sanaciju:

Ponovno postavljanje/zamjena zatega trijumfalnog luka kako bi se osigurala njihova odgovarajuća usidrenost na vanjsko lice uzdužnih zidova središnjeg broda.

Ojačanje veza pročelja s bočnim zidovima na gornjem koru i razini krova (vidi strategiju I1 u Tablici 3).

Table 3 – Possible general structural intervention strategies

Intervention	Description
I1	Use the timber floors and horizontal wood elements that are present in the structures to develop appropriate diaphragms that allow confining and tying together the whole system of masonry walls. This is achievable by means of additional horizontal steel elements (e.g., steel strips, L- or U-shape profiles), orthogonal and diagonal relative to the existing timber elements (e.g., beams of floors), bolted to the latter, in order to create mixed horizontal trusses. Such trusses should be connected to the surrounding walls by means of steel-tie beams (e.g., L- or U-shape profiles, or steel folded plates with stiffeners) regularly anchored along the perimeter of the walls through appropriate steel connectors that, ideally, should go across the entire (or close to entire) wall thickness.
I2	Improve the connections between intersecting walls (e.g., the façade and transverse walls), by inserting folded steel plates in the corners (preferably in each side of the walls) fastened to the walls with steel rods going across the entire wall thickness. In some cases, these plates might be hidden by the thickness of the existing plaster cover. In a situation where strategy I1 is used, these vertical folded plates can be connected (e.g., welded or bolted) to the horizontal surrounding steel-tie beams. All the steel elements should be protected against corrosion. Alternatively, steel connectors of the Cintec type ¹ (or equivalent) can be adopted to connect intersecting walls.
I3	In situations where the cover plaster has been removed from the walls (or is expected to be removed), the masonry can be strengthened using a reinforced plaster cover made of Textile Reinforced Mortar (TRM), using a glass, basalt or carbon fibre mesh attached to the masonry by connectors (e.g., stainless steel rebars or bolts), and covered by a Natural Hydraulic Lime (NHL 5). The principle is similar to the one used when doing a reinforced concrete jacketing (i.e., shotcrete) but using materials that are more compatible with the existing masonry in terms of strength, stiffness and chemical behaviour. When used simultaneously with strategies I1 and I2, this strategy leads to reinforced masonry walls that are expected to be more ductile and dissipative under earthquake action, which allows considering a lower seismic demand level in terms of strength.
I4	When the lateral resisting system is not sufficient and strategy I3 cannot be implemented, new lateral steel bracing systems (frames with diagonals) can be adopted as a reversible alternative to the use of reinforced concrete jacketing (i.e., shotcrete) of existing masonry. These new bracing systems can be placed wherever stiffness and/or strength is needed. From an architectural point of view, their visibility may be assumed as a new and different structural system, or it can be attached to existing masonry walls to have less visual prominence. In any case, this strategy should be adopted along with strategy I1 in order to ensure an appropriate connection with the existing masonry walls through the horizontal diaphragms.
I5	For vaults, mechanical fastenings and mortar injections should be done in zones where cracking occurred (i.e., crack stitching). In addition, the full strengthening of the vaults' extrados can be performed using reinforced plaster cover made of TRM, using a glass, basalt or carbon fibre mesh connected to the vault masonry using stainless steel rebars or bolts, and covered by a Natural Hydraulic Lime (NHL 5)

Regarding the Church of St Mary Magdalene in Sela, the following actions are suggested for its repair and rehabilitation:

Providing confinement at the level of vault rising. This might be achieved by means of a ring beam around the base vault or, in case it is not practically feasible, by introducing prestressed tendons around the drum above the nave windows.

Providing horizontal tie-rods (that would have to remain visible) across the triumphal arch, and making use of the upper choir parapet as a reinforced element to tie

the lower part of the shallow arch and the adjacent tower walls. Alternatively, this would also be possible by adding external buttresses.

Strengthening and consolidating the stone masonry of the walls above the bottom of the windows (see strategy I3 in Table 3).

Strengthening and consolidating the brick masonry of vaults (see strategy I5 in Table 3).

Strengthening and consolidating the towers (see strategy I2 in Table 3).



24 Damage in the upper zone of the tower (photo: X. Romão, July 2021)

Oštećenja u gornjoj zoni tornja (foto: X. Romão, srpanj 2021.)

Kontrolirano rušenje nestabilnih zona svoda i naknadna rekonstrukcija kojom se osigurava njihov kontinuitet na postojeću svodnu konstrukciju pomoću odgovarajućih pričvrstnih elemenata i injektiranja žbuke, eventualno dopunjeno armiranom žbukom kako je opisano u strategiji I5 (vidi tablicu 3). U rekonstruiranoj zoni svoda potrebno je osigurati dobru povezanost imposta s vertikalnom nosivom konstrukcijom.

Krovnu konstrukciju treba pregledati čim sigurnosni uvjeti to dopuste kako bi se utvrdilo jesu li potrebni daljnji zahvati.

Što se tiče crkve Svete Marije Magdalene u Selima, predlažu se sljedeće radnje za njen popravak i sanaciju:

Omeđivanje u razini svoda. To se može postići horizontalnim serklažem oko baze svoda ili, ako to nije izvedivo u praksi, uvođenjem prednapregnutih tetiva oko tambura iznad prozora središnjeg broda.

Postavljanje horizontalnih zatega (koje bi morale ostati vidljive) širinom trijumfalnog luka i korištenje parapeta kora kao ojačanog elementa za povezivanje donjeg dijela plitkog luka i susjednih zidova tornja. Alternativno, to bi također bilo moguće dodavanjem vanjskih upornjaka.



25 General view of the main chapel (photo: X. Romão, July 2021)

Opći pogled na glavnu kapelu (foto: X. Romão, srpanj 2021.)

Ojačanje i konsolidacija kamene zidane konstrukcije iznad dna prozora (vidi strategiju I3 u tablici 3).

Ojačanje i konsolidacija zidane konstrukcije svodova od opeke (vidi strategiju I5 u tablici 3).

Ojačanje i konsolidacija tornjeva (vidi strategiju I2 u tablici 3).

Osim ovih preporuka za konstrukcijske zahvate, u okviru konzervatorskih i sanacijskih radova treba uzeti u obzir i sljedeće opće preporuke:

Treba izbjegavati upotrebu morta na bazi portland cementa za žbukanje zidova i stropova jer: 1) soli će kontaminirati elemente zidane konstrukcije od opeke i pridonijeti degradaciji materijala i 2) ova vrsta morta ne dopušta prijenos vodene pare kroz zidanu konstrukciju, što može dovesti do pojave kondenzacije vlage unutar građevine.

U sanaciji zidnog oslika mortovi, koji se koriste za ispune (tj. pri restauraciji i zatvaranju dijelova koji nedostaju), moraju biti kompatibilni s postojećim mortovima, a kromatske ispune moraju slijediti uobičajene postupke konzerviranja i restauracije. Mortovi koji se koriste za injektiranje za konstrukcijsko zatvaranje pukotina na površinama sa zidnim oslikom moraju također biti kompatibilni s postojećim mortovima.

Aside from these recommendations for structural interventions, the following general recommendations should also be considered within the framework of the conservation and rehabilitation works:

The use of Portland cement-based mortars should be avoided in the plastering of walls and ceilings since i) salts will contaminate the brick masonry elements and contribute to their material degradation and ii) this type of mortar does not allow water vapour transmission across the masonry, which may lead to the occurrence of moisture condensation inside the building.

In the rehabilitation of mural paintings, the mortars used in gaps (i.e., in the restoration and completion of lost parts) must be compatible with the existing mortars and the chromatic filling of these gaps must follow the usual conservation and restoration procedures. Mortars that are used in injections for the structural consolidation of cracks in areas with mural paintings must be also compatible with existing mortars.

Timber structures and false ceilings should be adequately treated and protected against fire.

Although there is no systematized information proving that construction works are a source of fire incidents, it is known that many fires have occurred during the execution of conservation and rehabilitation works. Therefore, the implementation of additional fire safety measures during the execution of conservation and rehabilitation works is recommended, particularly in the roof areas. Examples of such measures are: i) forbidding smoking inside the construction zone; ii) ensuring that fire extinguishers are available in the roof areas during the works; iii) forbidding electrical overload of electrical cables and networks used for the construction works; iv) ensuring that light spots are turned off when leaving the workplaces (even if it is only for a short time period); v) strict control of sparking equipment usage in areas with timber elements; vi) do not turn off or cover any fire detection systems that may exist.

FINAL REMARKS

Based on the information gathered during the reconnaissance visit and interactions with representatives of the Croatian Ministry of Culture and Media and the University of Zagreb (Faculty of Civil Engineering), a series of strategic governance recommendations are presented in the following. These recommendations address several matters that go beyond the physical recovery of earthquake damage sustained by the cultural heritage constructions and provide further outlooks on issues that might be addressed to increase preparedness to future earthquakes and minimize their impacts in this sector.

The seismic safety of cultural heritage constructions: what should it be?

The concept of seismic safety is usually addressed based on available regulatory frameworks for seismic design or retrofit. However, when doing so, it must be kept in mind that such regulatory frameworks:

- may not be fully adequate for the seismic retrofit or rehabilitation of constructions that have important cultural and heritage values;

- provide procedures that are mostly focused on preserving the safety of the occupants and are less concerned with the preservation of cultural and heritage values.

These issues indicate that dealing with the seismic retrofit or rehabilitation of monuments or historic constructions may require approaches different than those found in available regulatory frameworks, as these themselves note.¹⁸ Furthermore, these regulatory frameworks also consider that the level of seismic safety that is expected to be reached by an existing construction can be lower than that of new constructions due to several aspects. As such, selecting the seismic retrofit or rehabilitation actions that should be implemented in cultural heritage constructions or the level of seismic performance they should target may require a case-by-case decision. This, in turn, will depend on the weight of different objectives that are related to the safety of people likely to use the cultural heritage construction and on the preservation of its authenticity and cultural values (i.e. defining a level of seismic safety for a cultural heritage construction should account for the impacts that interventions needed to attain that level of safety may have on the values and authenticity of that construction). Therefore, it is difficult to establish a level of seismic safety that should be targeted and decision-making in this type of situations should be based on the collective opinion of a multidisciplinary committee headed by the national/regional institution in charge of managing these constructions and preserving their values.

Making these decisions often demands a detailed and advanced assessment of the structural behaviour of these constructions under earthquake loading to be able to identify the damage mechanisms that are more likely to occur and understand the possible mitigation actions that can be implemented to improve their performance. This, in turn, requires detailed information about their relevant characteristics (geometry, material properties, level of conservation, etc.) and/or adequate approaches to account for the remaining sources of data uncertainty. Furthermore, developing the necessary analyses may require the use of international regulatory frameworks and guidelines for additional support and guidance.

¹⁸ E.g., see EC8-3, 2005

Potrebna je odgovarajuća protupožarna obrada i zaštita drvenih konstrukcija i ovješanih stropova.

Iako ne postoje sustavni podaci koji dokazuju da su građevinski radovi izvor požara, poznato je da su mnogi požari nastupili tijekom izvođenja konzervatorskih i sanacijskih radova. Stoga se preporučuje provedba dodatnih mjera zaštite od požara tijekom izvođenja konzervatorskih i sanacijskih radova, posebice u prostorima krovništva. Primjeri takvih mjera su: 1) zabrana pušenja unutar građevinske zone; 2) osiguravanje dostupnosti aparata za gašenje požara u prostoru krovništva tijekom radova; 3) zabrana električnog preopterećenja električnih kabela i mreža koje se koriste za građevinske radove; 4) osiguravanje isključivanja rasvjetnih tijela prilikom napuštanja radnog mjesta (čak i nakratko); 5) stroga kontrola upotrebe opreme koja iskri u područjima s drvenim elementima; 6) ne isključivati ili pokrivati bilo koji sustav za otkrivanje požara koji bi mogao postojati.

ZAVRŠNE NAPOMENE

Na temelju informacija prikupljenih tijekom izvidnih posjeta i interakcija s predstavnicima Ministarstva kulture i medija Republike Hrvatske te Sveučilišta u Zagrebu (Građevinski fakultet), u nastavku je predstavljen niz preporuka za strateško upravljanje. Te preporuke obrađuju nekoliko tema koja nadilaze fizičku sanaciju štete od potresa koju su pretrpjele građevine kulturne baštine i pružaju daljnje poglede na pitanja koja bi se mogla obraditi u svrhu povećanja spremnosti za buduće potrese i svođenja na najmanju moguću mjeru njihova utjecaja u ovom sektoru.

Seizmička sigurnost građevina kulturne baštine: kakva bi trebala biti?

Konceptu seizmičke sigurnosti obično se pristupa na temelju dostupnih regulatornih okvira za seizmičko projektiranje ili rekonstrukciju. Međutim, pritom se mora imati na umu da takvi regulatorni okviri:

možda nisu potpuno prikladni za seizmičku rekonstrukciju ili sanaciju građevina koje imaju važne kulturne i baštinske vrijednosti;

propisuju postupke koji su uglavnom usmjereni na očuvanje sigurnosti korisnika, a manje se bave očuvanjem kulturnih i baštinskih vrijednosti.

Ta pitanja upućuju na to da bavljenje seizmičkom rekonstrukcijom ili sanacijom kulturnih dobara ili povijesnih građevina može zahtijevati pristupe različitim od onih koji se nalaze u dostupnim regulatornim okvirima, kao što i oni sami navode.¹⁸ Nadalje, ti regulatorni okviri također uzimaju u obzir da razina seizmičke sigurnosti kakvu, očekivano, treba postići postojeća konstrukcija, može biti niža od razine novih konstrukcija zbog nekoliko

aspekata. U tom smislu, pri odabiru zahvata seizmičke rekonstrukcije ili sanacije koji bi trebao biti proveden u građevinama kulturne baštine ili pri odabiru razine seizmičke učinkovitosti koju bi one trebale postići, moglo bi biti potrebno odlučivanje od slučaja do slučaja. To će pak ovisiti o važnosti različitih ciljeva što se odnose na sigurnost ljudi koji će biti vjerojatni korisnici građevine kulturne baštine i na očuvanje njezine autentičnosti i kulturnih vrijednosti (tj. pri određivanju razine seizmičke sigurnosti za konstrukciju kulturne baštine treba uzeti u obzir utjecaje što ih zahvati potrebni za postizanje te razine sigurnosti mogu imati na vrijednosti i autentičnost te konstrukcije). Stoga je teško utvrditi ciljanu razinu seizmičke sigurnosti, a donošenje odluka u ovakvim situacijama trebalo bi se temeljiti na kolektivnom mišljenju multidisciplinarnog povjerenstva koje predvodi nacionalna/regionalna institucija zadužena za upravljanje ovim građevinama i očuvanje njihovih vrijednosti.

Za donošenje tih odluka često je potrebna detaljna i napredna procjena ponašanja konstrukcije tih građevina pod potresnim opterećenjem kako bi se mogli identificirati mehanizmi oštećenja za koje je vjerojatnije da će nastupiti te razumjeti mogući zahvati ublažavanja radi poboljšanja ponašanja konstrukcije. To pak zahtijeva detaljne informacije o relevantnim karakteristikama tih građevina (geometrija, svojstva materijala, razina očuvanosti itd.) i/ili odgovarajuće pristupe radi uzimanja u obzir preostalih izvora neodređenosti podataka. Nadalje, razvoj potrebnih analiza možda će zahtijevati primjenu međunarodnih regulatornih okvira i smjernica kao dodatnu podršku i vodilju.

Upravljanje rizikom od potresa za građevine kulturne baštine: nadilaženje aktivnosti rekonstrukcije i sanacije

Za provedbu odgovarajućeg okvira za upravljanje rizikom od potresa za kulturnu baštinu potrebna je opsežna strategija kakva obuhvaća više disciplina i uključuje niz radnji koje nadilaze razvoj rješenja za rekonstrukciju i sanaciju građevina kulturne baštine. Kao što je navedeno u prethodnom odjeljku, detaljna procjena ponašanja ovih konstrukcija pod potresnim opterećenjem zahtijeva dostupnost sveobuhvatnih informacija o njihovim relevantnim geometrijskim i materijalnim karakteristikama. Za to je potrebna usustavljena inventarizacija koje bi mogla pružiti informacije o određenim značajkama građevina kulturne baštine kao što su njihova geometrija, tehnike gradnje i konstrukcijski sustavi, svojstva građevinskih materijala, karakteristike dekorativnih elemenata i završnih obrada, nadogradnja i promjene konstrukcija tijekom

¹⁸ Vidi EC8-3, 2005.

Earthquake risk management of cultural heritage constructions: going beyond retrofit and rehabilitation actions

The implementation of an adequate framework for the earthquake risk management of cultural heritage requires a wide scope strategy that spans across multiple disciplines and involves a series of actions that go beyond the development of retrofit and rehabilitation solutions for cultural heritage. As referred in the previous section, the detailed performance assessment of these constructions under earthquake loading requires the availability of comprehensive information about their relevant geometrical and material characteristics. This triggers the need to have an inventory system that could provide information about certain features of cultural heritage constructions such as their geometry, the construction techniques and structural systems they involve, the properties of building materials, the characteristics of decorative elements and finishes, evolution and alterations of the constructions over time, and damaged or degraded features they may exhibit.¹⁹ Collecting this information presents several challenges due to the resources it can involve and the complexity of certain cultural heritage constructions. However, this information is vital for performing a realistic assessment of the conservation and/or retrofitting needs in pre-event scenarios, as well as for developing adequate repair and/or reconstruction operations guided by principles highlighting the preservation of authenticity and values in post-event scenarios.²⁰ In pre-event scenarios, the availability of this information and knowledge can help prioritizing conservation and maintenance actions that, in turn, can enhance the resilience potential of cultural heritage and actively contribute to reduce future earthquake losses in cultural heritage.

Developing this type of inventory system requires enhancing the management capacity of the institution in charge of the preservation of cultural heritage constructions, namely in terms of assigning it with the necessary resources. Still, the development of this inventory system, along with the implementation of a regular monitoring plan of cultural heritage constructions to actively detect and prioritize conservation and maintenance actions, are key points in a strategy that targets the enhancement of cultural heritage resilience to earthquakes, as well as to other disasters.

The availability of the referred inventory system is also key to enhance the capacity of practicing engineers to deal with the seismic performance assessment and the rehabilitation of cultural heritage constructions. Still, efforts should also be dedicated to the development of practical training can capacity building programmes that address the detailed performance assessment of these constructions under earthquake loading. Such programmes would allow

the practicing engineering community to become more familiar with traditional materials, structural systems and construction techniques, and would provide it with the necessary knowledge and tools to perform the referred analyses.

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¹⁹ ICOMOS, 2003

²⁰ ICOMOS, 2017

²¹ Instituto de I&D em Estruturas e Construções, 2020.-2023

vremena te moguća oštećenja ili degradirana obilježja.¹⁹ Prikupljanje tih informacija nosi nekoliko izazova zbog potrebnih resursa i složenosti određenih građevina kulturne baštine. Međutim, te su informacije ključne za izvođenje realne procjene potreba za zahvatima konzerviranja i/ili rekonstrukcije u scenarijima prije događaja, kao i za pripremu odgovarajućih zahvata popravka i/ili rekonstrukcije vođenih načelima koja naglašavaju očuvanje autentičnosti i vrijednosti u scenarijima nakon događaja.²⁰ U scenarijima prije događaja, dostupnost ovih informacija i znanja može pomoći u davanju prioriteta zahvatima konzerviranja i održavanja koji, zauzvrat, mogu poboljšati potencijal otpornosti kulturne baštine i aktivno pridonijeti smanjenju budućih gubitaka kulturne baštine uslijed potresa.

Za izradu takvog usustavljenog inventara potrebno je jačanje upravljačkih kapaciteta ustanove nadležne za očuvanje građevina kulturne baštine, i to u smislu osiguravanja potrebnih sredstava. Ipak, razvoj takvog usustavljenog inventara, zajedno s provedbom redovnog plana praćenja građevina kulturne baštine radi aktivnog otkrivanja i određivanja prioriteta zahvata konzerviranja i održavanja, ključne su točke strategije čiji je cilj unaprijediti otpornosti kulturne baštine na potrese, kao i na druge katastrofe.

Dostupnost navedenog usustavljenog inventara također je ključna za podizanje kapaciteta inženjera koji se u praksi bave procjenom seizmičkih svojstava građevina kulturne baštine i njihovom sanacijom. Ipak, napori bi također trebali biti usmjereni na programe praktične obuke za razvoj kapaciteta kakvi se bave detaljnom procjenom ponašanja ovih konstrukcija pod potresnim opterećenjem. Takvi programi omogućili bi inženjerskoj zajednici da se bolje upozna s tradicionalnim materijalima, konstrukcijskim sustavima i tehnikama gradnje te bi joj pružili potrebno znanje i alate za obavljanje navedenih analiza.

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1 Vatrogasna postrojba u suradnji s Gradskim zavodom prije skidanja ukrasne vaze s krova zgrade Račkoga 9 (fototeka Gradski zavod za zaštitu spomenika kulture i prirode, dalje - GZZSKP 2020.)

The fire department in cooperation with the City Institute before removing the decorative vase from the roof of the building at Račkoga 9 (City Institute for the Conservation of Cultural and Natural Heritage photo archive, 2020)