Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

THE CASE STUDY OF PRINCE RUDOLF INFANTRY BARRACKS - ASSESSMENT, MODELLING AND RECONSTRUCTION

Boja Čačić Šipoš (1), Nataša Ivanišević (2), Mija Klasić (3), Luka Lulić (4), Ivan Matorić (5), Mislav Stepinac (6)

(1) *Civil engineer, Peoples Associates Structural Engineers, e-mail address: boja.cacic.sipos@pase.com*
(2) *Architect, A&A Architects, e-mail address: natasa@aa-architects.net*
(3) *Civil engineer, Peoples Associates Structural Engineers, e-mail address: mija.milic@pase.com*
(4) *PhD student, University of Zagreb Faculty of Civil Engineering, e-mail address: luka.lulic@grad.unizg.hr*
(5) *Civil engineer, Peoples Associates Structural Engineers, e-mail address: ivan.matoric@pase.com*
(6) *Assistant Professor, University of Zagreb Faculty of Civil Engineering, e-mail address: mislav.stepinac@grad.unizg.hr*

Abstract

The procedure of a detailed condition assessment of the building under heritage protection in Zagreb is presented. A detailed historical background of the case study building is shown, and observed damage and conducted in situ tests are discussed. The nonlinear static seismic analysis performed in the 3Muri software is extensively elaborated. Four different levels of reconstruction according to new Croatian law are briefly presented. Additionally, several strengthening scenarios are proposed with various strengthening techniques. The renovation of the case study building is presented through extensive photo documentation. The problems in renovations of culturally protected buildings in a specific case study are raised.

Keywords: assessment, masonry, renovation, NDT, case study, 3Muri

1. Introduction

Unreinforced masonry (URM) structures are primarily located in European urban centres and are highly vulnerable to earthquake excitations. After the Zagreb earthquake in 2020, they suffered significant damage and should be upgraded, renovated, or demolished [1]–[3]. This paper presents the procedure for a detailed condition inspection, modelling, and reconstruction of a building under cultural heritage protection. The case study building was damaged in the earthquake and needs to be renovated according to the new Croatian laws to ensure the safe and functional future use of the building. The case study building is located within the historic complex of buildings in the western part of the Zagreb 'Lower Town", the so-called Infantry Barracks of Prince Rudolf. The entire complex of the Rudolf Barracks is protected as an immovable individual cultural property and is registered in the Register of Cultural Heritage of the Republic of Croatia. The protection of the complex refers to the main building and the entire area of the former pedestrian barracks with the existing high-quality green areas, undeveloped areas, and peripheral buildings of high environmental value. The Rudolf Barracks complex is located in Protection Zone A of the historical and urban unit of the City of Zagreb, which is protected as a cultural asset and entered in the Register of Cultural Heritage of the Republic of Croatia - List of Protected Cultural Heritage.

The infantry barracks complex was built in the period from 1887 to 1889, according to the project of Viennese architects Franz Gruber and Carl Voelckner. The complex consisted of 13 buildings, most of which were two-story buildings, and was named after the son of Emperor Franz Joseph I and Empress Sisi, Prince Rudolf [4],[5]. The entire complex was built within 15 months after Prince Rudolf laid the foundation stone. The construction of the complex was triggered by tensions related to the Austro-Hungarian occupation of Bosnia and Herzegovina and the need to accommodate the army.

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

Figure 1. Case study building

The case study building is a public-purpose building with a rectangular floor plan of 25.18 m × 11.42 m and a height of approximately 15.50 m. The building has five floors, and all are used as office space. The building has undergone minor changes in the original geometry and space over time and has been properly maintained. More information about the building can be found in the paper by Milić et al. [6].

2. Condition assessment and modelling of the case study building

Various non-destructive, semi-destructive, and destructive methods are used to assess existing URM structures. More information about assessment methods can be found in [7],[8].

The particular case study was inspected after the earthquake on 22 March, 2020. It was assigned the usability mark PN2. The mark PN2 refers to buildings with moderate damage without the risk of collapse, but the usability is questionable due to the potential risk of collapse of some elements [9],[10]. The building did not experience severe damage, but several parts of the structure should be repaired. The more significant damage was observed at the connection of partition and load-bearing walls, as well as at the connection of walls and ceilings. The damage observed is not surprising since at the connections of partition and load-bearing walls, as well as walls and ceilings, there is a discontinuity of materials and contact of different materials with different behavior, thus causing different displacements that cause cracks (Figure 2). This inspection established a conservation guideline for repairing load-bearing and partition walls, staircases, and floor structures [6].

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

Figure 2. Observed damage

2.1 Flat-jack method for obtaining mechanical properties of masonry

The method is based on the principle of introducing stress into the masonry using metal flat-jacks of a semioval shape that is inflated like a balloon. A more detailed description of the flat-jack method can be found in [11],[12]. According to the tests (Figure 10), the following values were obtained: compressive stress state in masonry at test location σ_0=0.46 N/mm^2 (used for model calibration regarding weight distribution), modulus of elasticity E = 1469.5 N/mm^2 (used for wall stiffness definition), initial shear strength f_{v0} = 0.323 N/mm^2 (used for wall shear resistance definition) and coefficient of friction μ = 0.447. The whole procedure is shown in Milić et al. [6].

2.2 Numerical modelling

The modelling was done with the software 3Muri [13]. Modelling of the building in 3Muri software is done by inserting walls, columns, and beams, which are then discretized into macro elements. There are two types of macro elements, and these are the piers and parapets, where all the damage is concentrated. Parts of the wall, which are often undamaged, are defined as rigid nodes connecting the former two [34]. The mathematical concept underlying the use of macroelements makes it possible to determine the mechanism of collapse, i.e., the mechanism of damage. The damage may be due to shear in the central part of the macroelements or to combined compressive and bending stress in the peripheral parts of the macroelements [14].

Horizontal diaphragms are modelled using floor elements connected by three-dimensional nodes. The loads on the horizontal diaphragms (used only for mass calculation and distribution) are perpendicular to the floor level, and the seismic action is in the direction of the floor level. For this reason, the horizontal diaphragms can be modelled as axially stiff or flexible but without bending stiffness. Such shaping of the horizontal diaphragms is permissible because their main function is to absorb the horizontal actions from the seismic action and transmit them to the vertical load-bearing elements [15]. 3Muri assumes good wall-to-wall and wall-to-floor connections, i.e., box behavior, which is desirable but often unrealistic in existing structures. Therefore, the modelling assumes that the damaged masonry has been restored to its original, undamaged condition by methods such as grouting and that the necessary measures have been taken to ensure the box behavior of the observed structure. In addition,

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

3Muri allows for out-of-plane failure analysis of local mechanisms in a separate module. This is extremely useful since the box behavior can only account for in-plane masonry failure. More about the analysis of local mechanisms in 3Muri can be found in [16].

Figure 3 shows a 3D model of the building in 3Muri. More about modelling can be found in the paper by Milić et al. [6]. Three-dimensional model with damage for the near-collapse limit state: (a) x-direction; (b) y-direction can be seen in Figure 4.

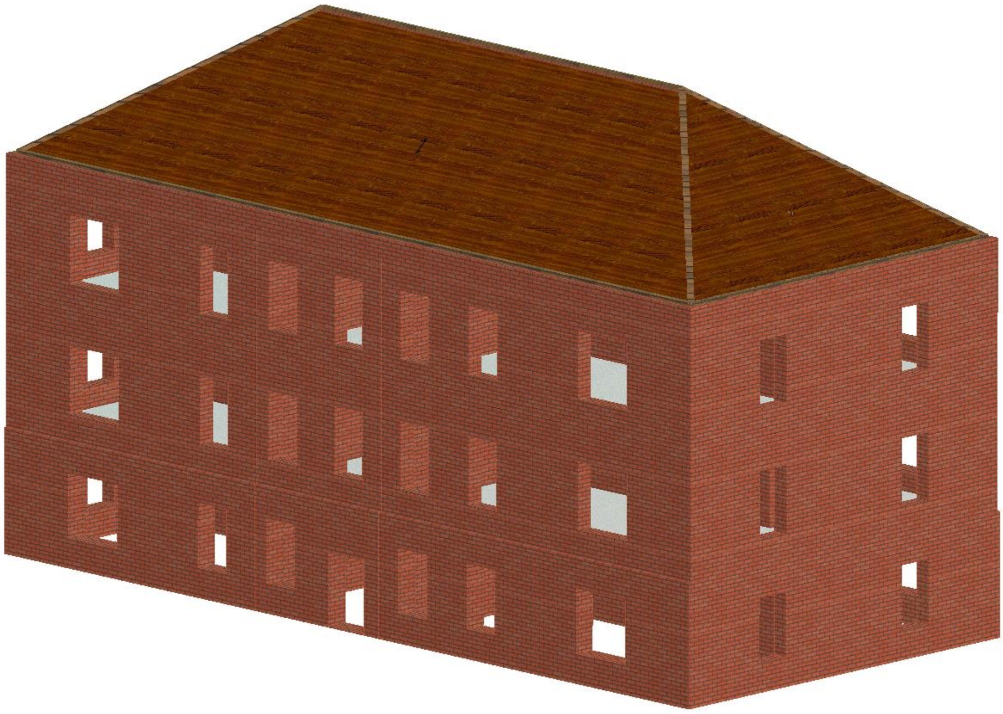
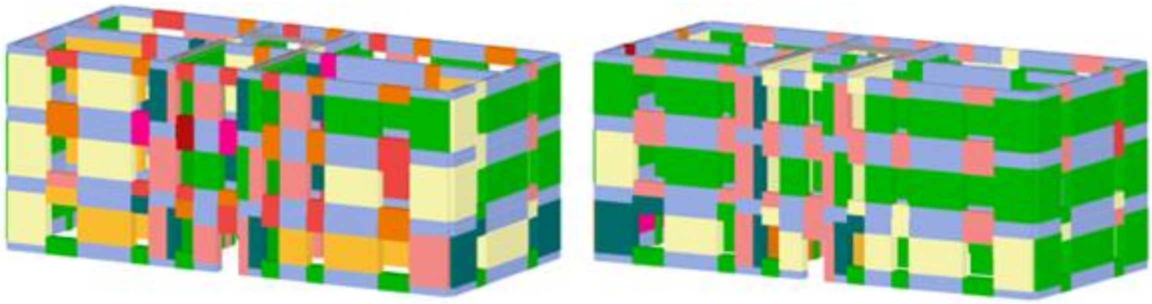


Figure 3. 3Muri model of observed building



a) b)

Figure 4. 3Muri model – observed damage in the model

3. Renovation strategies

For the successful renovation of buildings damaged by the earthquake, appropriate measures must be taken to repair and strengthen the building without compromising the mechanical properties of the material and the properties of the structure, which contribute to the durability of the building. Following the obtained results, a proposal of measures for the repair and reinforcement of buildings is given. Measures should follow the seismic design and be in line with the conservation and restoration rules [17],[18].

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

As a measure of repair and reinforcement of the walls of the building, it is recommended to reinforce load-bearing walls by, e.g., FRCM system or concrete jacketing. Figure 5 shows a proposal for reinforcing load-bearing walls. To obtain good resistance in the transverse direction (y-direction), it is proposed to add new load-bearing walls with a minimum thickness of 38 cm. In addition, it is proposed to remove the brick partition walls and replace them with a drywall system. Figure 6 shows a proposal for the position of the new load-bearing walls and a proposal for the removal and replacement of partition walls. In addition to the above methods, it is necessary to strengthen the ceiling structure. Therefore, to repair and reinforce the wooden ceiling structure, a thin reinforced concrete compression slab is proposed to increase the load-bearing capacity and stiffen the structure (rigid). All vaulted elements and vaults in the basement are to be maintained in their original form, with the possibility of reinforcing them with carbon fiber and maintaining the original proportions of the vaults to preserve the building's original construction and design features. Figure 7 shows the strengthening of the timber roof structure.

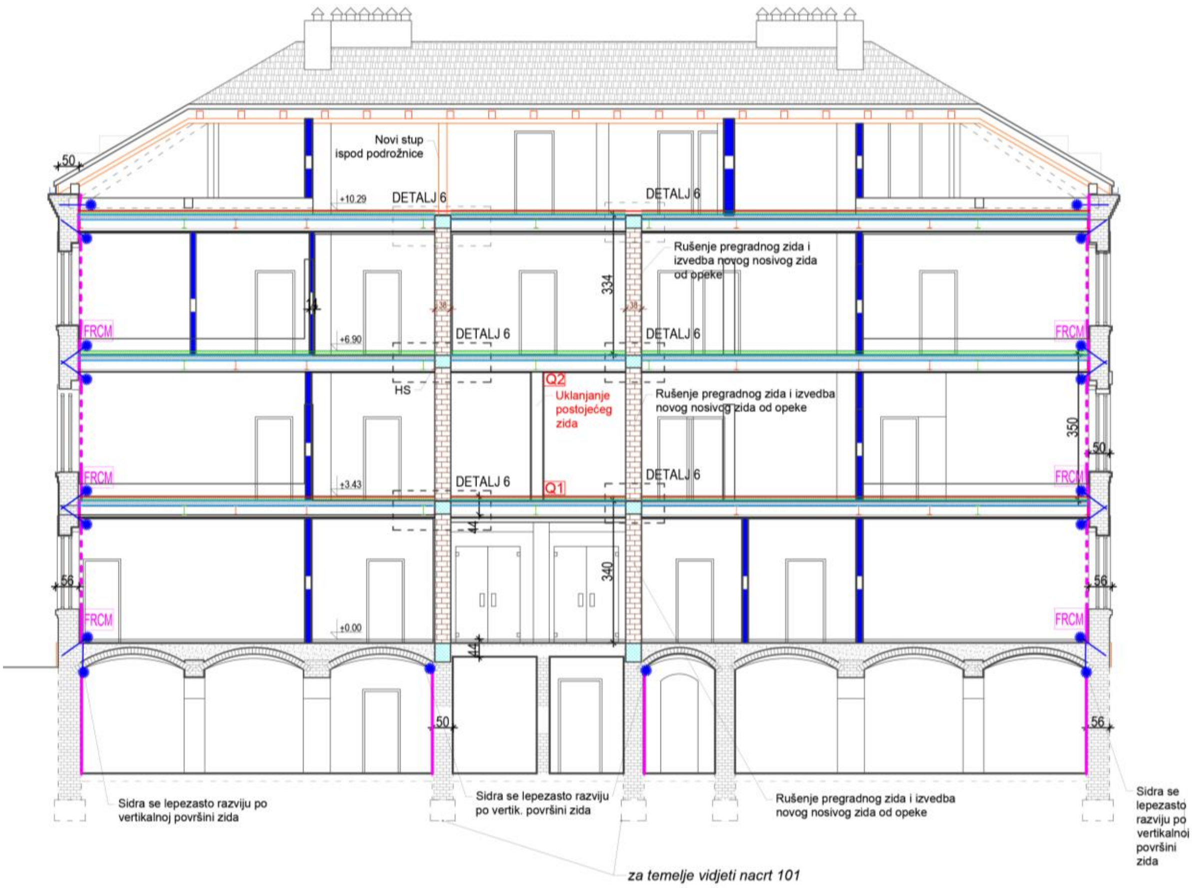


Figure 5. Strengthening proposal

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

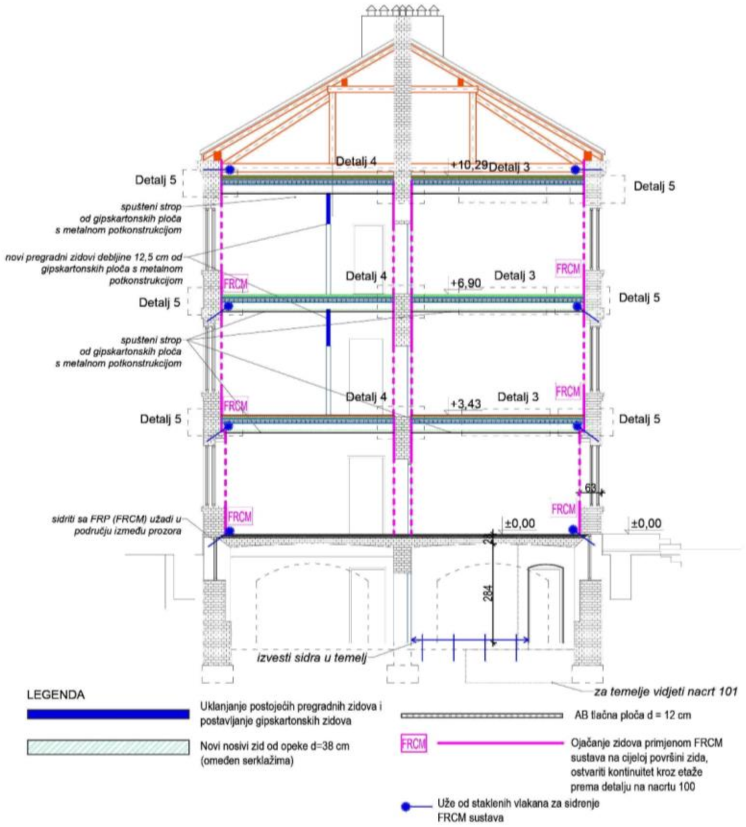


Figure 6. Proposal for the position of the new load-bearing walls and proposal for the removal and replacement of partition walls

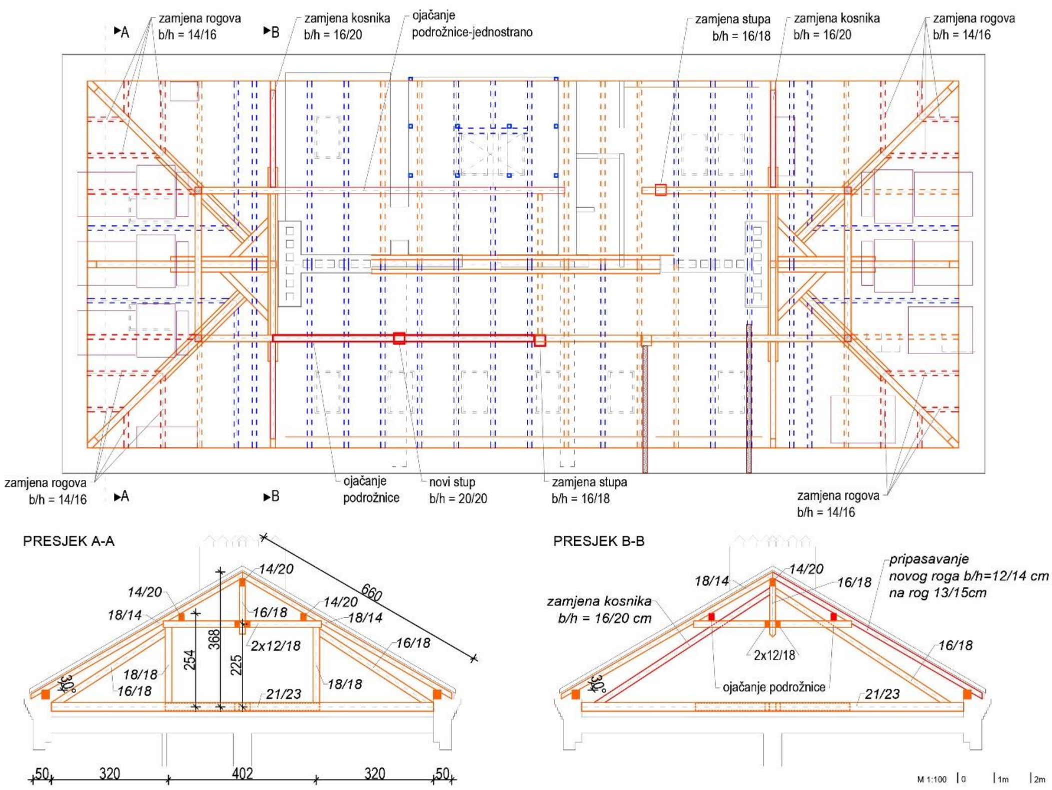


Figure 7. Strengthening of the roof structure

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

The renovation of the building started in June 2022. The plaster was removed from all the elements (Figure 8), and the masonry joints were cleaned. A new stiff diaphragm is placed (Figure 8).

Figure 8. Plaster removal and preparations for strengthening

Currently, seismic retrofit with FRCM system is underway. The procedure includes the removal of all existing plaster coats from the walls with complete repointing of the walls [19]. Also, the removal of all partition walls made of unreinforced masonry and replacement with drywall systems is underway.

New confined masonry walls as lateral force-resisting systems have been added to provide a continuous and competent load path from the top of the structure to the foundation. A new existing staircase that doesn't meet the actual technical requirements is planned to be replaced with a new steel stairway that will be completely independent of the rest of the building structure.

New rigid diaphragms have replaced existing flexible diaphragms as steel-concrete composite structures, which have been proven with high resistance to seismic and cyclic loading [20] and to secure evenly distribution story shear and torsional moment (Figure 9). On top of the concrete architectural floor, layers are planned to be installed: topping slab with sound insulation, PE foil, cement screed, and finishing skin. During the construction work, it was revealed that some of the elements were not in the right place or not built in a predicted manner, so it was essential to have construction administration included all the time. For example, it was noted that existing steel members were not where they were supposed to be, nor did the number of steel members match the previous design, so it was crucial to have designers involved in the construction so the site would not be paused.

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

Figure 9. New stiff diaphragm

New bracing elements in longitudinal directions are included to improve the roof structure's lateral system. Some decay effects due to dry and wet rot on the roof elements are noted, which caused some rafters to be changed completely [21]. This retrofit was planned to change thermal insulation entirely and use a warm roof system to improve envelope performance.

During the design process, technical solutions were driven by the idea to use as many as possible or, to say, barre minimum of invasive methods for this historical building and to preserve the layout as much as possible not to interfere with its functionality. This project envisioned appropriate materials for the structural retrofit of a historical building to enable the preservation and presentation of the original construction characteristics in the interior of the building.

For this building, besides the seismic retrofit, the plan is to complete a renovation with a new heating and cooling system. Also, a new ventilation system is planned to be implemented as a centralized system installed in the Attic of the building with new dormers for air intake and exhaust on the north and south sides of the roof. New AC wall units are planned to be installed in the basement and attic, while on all other floors, they are planned to be ceiling units.

Complete new electrical installations are planned to be installed, a new hydrant network, new fire suppression and detection system, and new plumbing and drainage systems are planned. After retrofitting and renovation, the building will be ‘’upgraded’’ to new regulatory requirements that each new building needs to meet.

4. Discussion and conclusions

Determining the actual seismic behavior of existing masonry structures is of great importance for future management and the economic and purposeful strengthening of the load-bearing structure [22]. Modern software solutions and design methods are an essential part of the assessment, but they are only as useful as the input parameters are reliable [23]. In addition to strengthening, it is of great importance to consider aspects of energy efficiency [24] and the preservation of cultural heritage.

This research presents a simple case study of a whole procedure of seismic updating of an existing masonry building. The results obtained with the 3Muri software and the simplified method show that the case study building does not meet the conditions of limited damage, significant damage, and near collapse with return periods of 95 years, 225 years, and 475 years, respectively. Therefore, in addition to the structure's condition assessment and seismic design, a proposal for measures to repair and strengthen the structure per current legislation and new regulations was prepared.

When designing an engineering solution for the renovation and strengthening of the seismic safety of the protected heritage building, strengthening methods that are least invasive to the historic structure

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

should be used, applying appropriate materials and methods to allow the preservation and presentation of the original exterior and interior building features.

Retrofits must consider and improve the energy efficiency of the building and preserve the architectural and historical values of the protected heritage while ensuring the safe and functional use of the building. Earthquake-related measures, visible or not, should respect and visually harmonize with the character and integrity of the heritage site. The seismic system should be reversible to the extent possible so that more advanced seismic measures can replace it in the future.

Acknowledgements

Croatian Science Foundation contributed to this paper's preparation through the ARES project: Assessment and rehabilitation of existing structures – development of contemporary methods for masonry and timber structures, grant number UIP-2019-04-3749, project leader: Mislav Stepinac.

References

[1] Stepinac, M.; Lourenço, P. B.; Atalić, J.; Kišiček, T.; Uroš, M.; Baniček, M.; Šavor Novak, M. Damage Classification of Residential Buildings in Historical Downtown after the ML5.5 Earthquake in Zagreb, Croatia in 2020. Int. J. Disaster Risk Reduct. 2021, 56, 102140. https://doi.org/https://doi.org/10.1016/j.ijdrr.2021.102140.

[2] Moretić, A.; Stepinac, M.; Lourenço, P. B. Seismic Upgrading of Cultural Heritage – A Case Study Using an Educational Building in Croatia from the Historicism Style. Case Stud. Constr. Mater. 2022, 17, e01183. https://doi.org/10.1016/J.CSCM.2022.E01183.

[3] Novak, M. Š.; Uroš, M.; Atalić, J.; Herak, M.; Demšić, M.; Baniček, M.; Lazarević, D.; Bijelić, N.; Crnogorac, M.; Todorić, M. Zagreb Earthquake of 22 March 2020 – Preliminary Report on Seismologic Aspects and Damage to Buildings. Gradjevinar 2020. https://doi.org/10.14256/JCE.2966.2020.

[4] Knežević, S.: Povijest Područja Bivše Rudolfove Vojarne i Trga Francuske Republike u Zagrebu; Godišnjak Zaštite Spomenika Kulture Hrvatske, 22-23 (1996-1997), 57-72, Institut Za Povijest Umjetnosti, Zagreb, 1997.

[5] Knežević, S.: Zagrebačke Planirane Vojarne Iz Doba Habsburške Monarhije; Institut Za Povijest Umjetnosti, Zagreb, 2007.

[6] Milić, M.; Stepinac, M.; Lulic, L.; Ivanisevic, N.; Matoric, I.; Cacic Sipos, B. Assessment and Rehabilitation of Culturally Protected Prince Rudolf Infantry Barracks in Zagreb after Major Earthquake. Buildings 2021.

[7] Krolo, J.; Damjanović, D.; Duvnjak, I.; Frančić Smrkić, M.; Bartolac, M.; Koščak, J. Metode Određivanja Mehaničkih Svojstava Ziđa. Građevinar 2021, 73 (2), 127–140. https://doi.org/https://doi.org/10.14256/JCE.3063.2020.

[8] Stepinac, M.; Kisicek, T.; Renić, T.; Hafner, I.; Bedon, C. Methods for the Assessment of Critical Properties in Existing Masonry Structures under Seismic Loads-the ARES Project. Appl. Sci. 2020, 10 (5). https://doi.org/10.3390/app10051576.

[9] Uroš, M.; Šavor Novak, M.; Atalić, J.; Sigmund, Z.; Baniček, M.; Demšić, M.; Hak, S. Procjena Oštećenja Građevina Nakon Potresa - Postupak Provođenja Pregleda Zgrada. Građevinar 2020, 72 (12), 1089–1115.

[10] Hafner, I.; Lazarević, D.; Kišiček, T.; Stepinac, M. Post-Earthquake Assessment of a Historical Masonry Building after the Zagreb Earthquake–Case Study. Buildings 2022, 12 (3). https://doi.org/10.3390/buildings12030323.

[11] Gregorczyk, P.; Lourenço, P. B. A Review on Flat-Jack Testing A Review on Flat-Jack Testing. 2019, No. January 2000.

[12] Lulić, L.; Ožić, K.; Kišiček, T.; Hafner, I.; Stepinac, M. Post-Earthquake Damage Assessment-Case Study of the Educational Building after the Zagreb Earthquake. Sustain. 2021. https://doi.org/10.3390/su13116353.

[13] S.T.A. DATA, 3Muri Program, Release XXX. Www.Stadata.Com.

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.94

[14] Lagomarsino, S.; Penna, A.; Galasco, A.; Cattari, S. TREMURI Program: An Equivalent Frame Model for the Nonlinear Seismic Analysis of Masonry Buildings. Engineering Structures. 2013, pp 1787–1799. https://doi.org/10.1016/j.engstruct.2013.08.002.

[15] Mirra, M.; Ravenshorst, G.; van de Kuilen, J.-W. Comparing In-Plane Equivalent Shear Stiffness of Timber Diaphragms Retrofitted with Light and Reversible Wood-Based Techniques. Pract. Period. Struct. Des. Constr. 2021. https://doi.org/10.1061/(asce)sc.1943-5576.0000602.

[16] Salaman, A.; Stepinac, M.; Matorić, I.; Klasić, M. Post-Earthquake Condition Assessment and Seismic Upgrading Strategies for a Heritage-Protected School in Petrinja, Croatia. Build. 2022, Vol. 12, Page 2263 2022, 12 (12), 2263. https://doi.org/10.3390/BUILDINGS12122263.

[17] Funari, M. F.; Mehrotra, A.; Lourenço, P. B. A Tool for the Rapid Seismic Assessment of Historic Masonry Structures Based on Limit Analysis Optimisation and Rocking Dynamics. Appl. Sci. 2021, 11 (3). https://doi.org/10.3390/app11030942.

[18] Funari, M. F.; Silva, L. C.; Mousavian, E.; Lourenço, P. B. Real-Time Structural Stability of Domes through Limit Analysis: Application to St. Peter's Dome. Int. J. Archit. Herit. 2021, 1–23. https://doi.org/10.1080/15583058.2021.1992539.

[19] Kišiček, T.; Stepinac, M.; Renić, T.; Hafner, I.; Lulić, L. Strengthening of Masonry Walls with FRP or TRM. Gradjevinar 2020, 72 (10), 937–953. https://doi.org/https://doi.org/10.14256/JCE.2983.2020.

[20] Stepinac, M.; Rajčić, V.; Barbalić, J. Influence of Long Term Load on Timber-Concrete Composite Systems. Gradjevinar 2015, 67 (3). https://doi.org/10.14256/JCE.1170.2014.

[21] Stepinac, M.; Rajčić, V.; Barbalić, J. Pregled i Ocjena Stanja Postojećih Drvenih Konstrukcija. Gradjevinar 2017, 69 (9), 861–873. https://doi.org/10.14256/JCE.1994.2017.

[22] Stepinac, M.; Skokandić, D.; Ožić, K.; Zidar, M.; Vajdić, M. Condition Assessment and Seismic Upgrading Strategy of RC Structures—A Case Study of a Public Institution in Croatia. Buildings 2022, 12 (9), 1489. https://doi.org/10.3390/buildings12091489.

[23] Colombo, C.; Savalle, N.; Mehrotra, A.; Funari, M. F.; Lourenço, P. B. Experimental, Numerical and Analytical Investigations of Masonry Corners: Influence of the Horizontal Pseudo-Static Load Orientation. Constr. Build. Mater. 2022, 344, 127969. https://doi.org/10.1016/j.conbuildmat.2022.127969.

[24] Milovanovic, B.; Bagaric, M.; Gaši, M.; Stepinac, M. Energy Renovation of the Multi-Residential Historic Building after the Zagreb Earthquake - Case Study. Case Stud. Therm. Eng. 2022, 38 (July). https://doi.org/10.1016/j.csite.2022.102300.