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.2023.97

RETROFITTING OF SACRAL BUILDINGS AFTER THE RECENT EARTHQUAKES IN CROATIA

David Anđić (1), Maja Baniček (2), Tamara Horvat (3), Borna Doračić (4), Juraj Pojatina (5), Mislav Stepinac (6), Ana Baričević (7)

(1) Structural Engineer, Studio Arhing ltd., david@studio-arhing.com
(2) Postdoctoral Researcher, University of Zagreb Faculty of Civil Engineering, maja.banicek@grad.unizg.hr
(3) Structural Engineer, Studio Arhing ltd, tamara@studio-arhing.com
(4) Structural Engineer, Studio Arhing ltd., borna@studio-arhing.com
(5) Structural Engineer, Studio Arhing ltd., juraj@studio-arhing.com
(6) Assistant Professor, University of Zagreb Faculty of Civil Engineering, mislav.stepinac@grad.unizg.hr
(7) Associate Professor, University of Zagreb Faculty of Civil Engineering, ana.baricevic@grad.unizg.hr

Abstract

After the Petrinja earthquake in December 2020, 442 individual immovable cultural assets were damaged, including 124 cultural heritage buildings that suffered severe structural damage. The largest number of damaged cultural heritage assets concern sacral buildings, mainly churches and chapels. In this paper, a brief overview of the damage to several sacral buildings after the earthquakes in Croatia is presented. The failure mechanism and typical damages are presented graphically. In addition, special emphasis is placed on the complete retrofitting of a damaged church. The condition assessment, numerical modelling and full seismic retrofit of the selected church is shown.

Keywords: Retrofitting, Assessment, Heritage buildings, Church, Earthquake

1. Introduction

Following the Zagreb earthquake in March of 2020, a destructive 6.2 magnitude earthquake struck Croatia again in December of 2020. The Sisak-Moslavina county suffered the most severe consequences; many historical and cultural buildings were severely damaged [1]. According to the data collected by the Croatian Center for Earthquake Engineering (HCPI – in Croatian), more than 57 000 buildings were damaged [2]. The forms and features of the architectural heritage in the affected area are influenced by the attributes of a militarized frontier under the Habsburg monarchy [3]. The Sisak-Moslavina county is characterized by small historical settlements with prominent parish churches, chapels, and isolated aristocratic estates with palaces [4]. In Sisak-Moslavina county alone, 308 immovable cultural assets with 4,416 houses in cultural and historical areas were damaged. According to the data of the World Bank report [5] and HCPI [2], 206 religious buildings were damaged by the earthquake, 52 were severely damaged or demolished. Most churches suffered severe damage to the load-bearing walls, vaults, and bell tower walls, compromising the overall stability of the buildings. Several churches suffered collapse of parts of the building, usually the bell tower, the roof, the vaults, and parts of the perimeter walls. The degree and severity of the damage was classified according to EMS-98 [6]. In February 2021, the new Law on the Reconstruction of Earthquake-Damaged Buildings in the City of Zagreb, Krapina-Zagorje County, Zagreb County, Sisak-Moslavina County and Karlovac County was enacted [7]. The Law and Amendment to the Technical Regulation for Building Structures (Official Gazette 75/2020) [8] defines four different levels of reconstruction of earthquake-damaged structures in terms of achieved mechanical resistance and stability. In this paper, severely damaged churches (3 case studies) are presented. The focus of the study is on the condition assessment procedures and retrofitting methods following the holistic approach of the international council on monuments and sites (ICOMOS).

2. Condition assessment of selected churches

2.1 Historical background

The materials and geometry of the damaged churches coincide with the time and area of construction. The church of St Michael in Gračani (Zagreb) is a 17th century masonry structure with stone walls and brick arches and cross vaults. St. George's church and St. Mary's chapel are located in Mala Gorica, approximately 60 km from Zagreb (Figure 1). St. George's church is a masonry structure with stone walls, arches and cross vaults from the 18th century, while St. Mary's chapel is a 20th century structure with masonry walls and a wooden barrel vault, hanged onto the roof structure. Floor plans and sections are shown in Figures 2, 3 and 4.

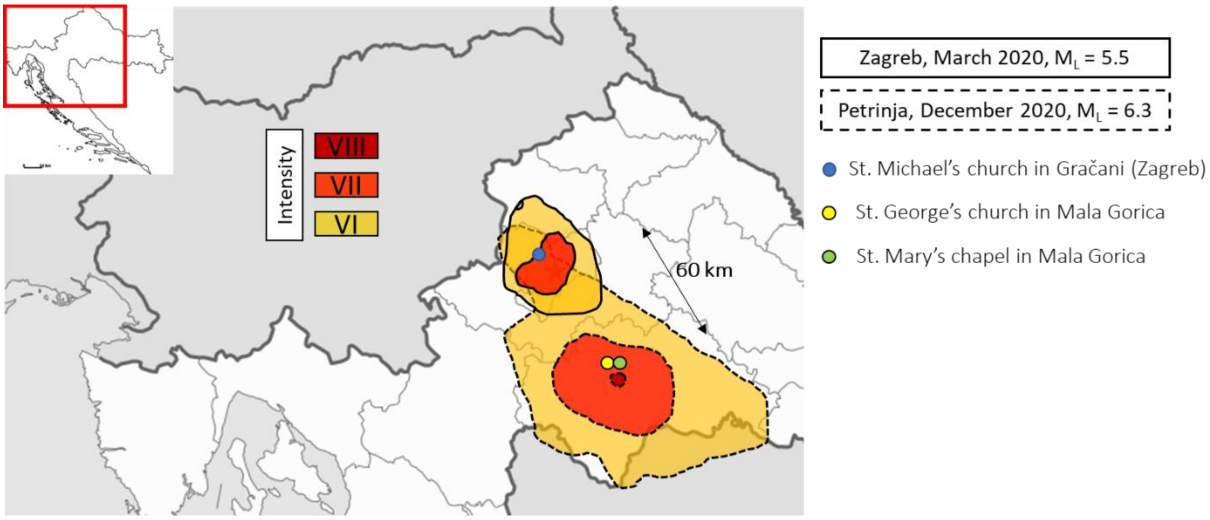


Figure 1. Map of church locations

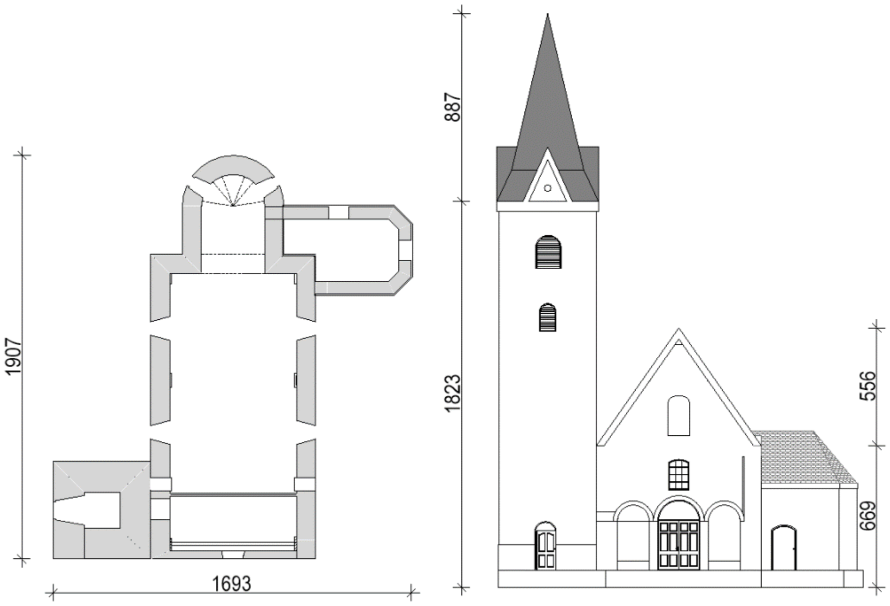


Figure 2. The Church of St. Michael in Gračani (architectural blueprint made in 2020.)

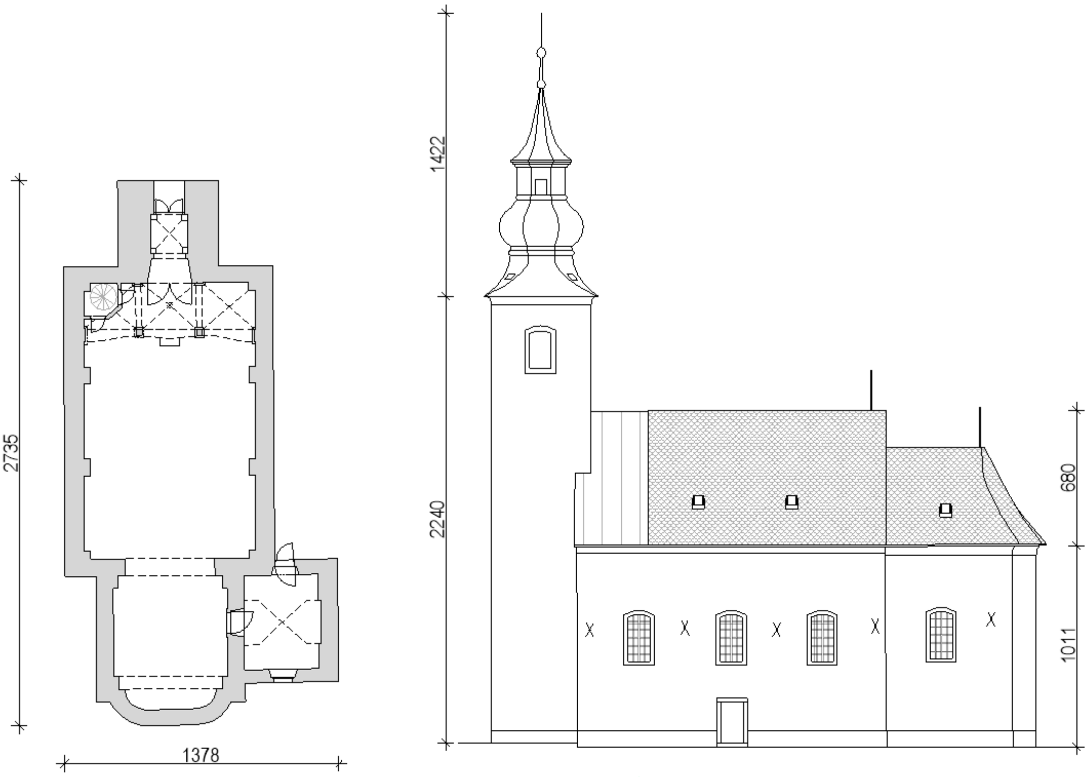


Figure 3. The Church of St. George in Mala Gorica (architectural blueprint made in 2021.)

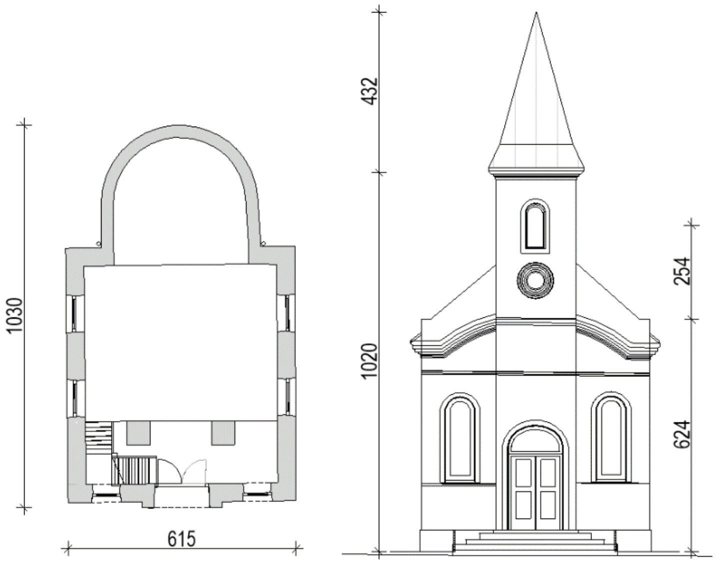


Figure 4. St. Mary’s chapel in Mala Gorica (architectural blueprint made in 2022.)

As already mentioned, traditional materials were used. Multi-leaf stone or solid brick masonry with minimal lime mortar for the walls. Arches and vaults are made of stone, solid bricks or timber. Roof structures are mostly made of softwood.

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.97

2.2 Visual inspection

Visual inspection is the first step in condition assessment of an earthquake-damaged building. The result of the visual inspection is information about structural and/or mechanical damage to the structure (such as cracks, deformations and deflections), which are used to identify failure mechanisms.

2.2.1 The Church of Saint Michael, Gračani

The church of Saint Michael in Gračani (Zagreb) has suffered substantial damage to the tower. Diagonal cracks and local deviation from the verticality of the tower, Figure 5, clearly suggested the main failure mechanism, in-plane shear/tension failure of the tower walls. The damage was classified as level 3 in EMS-98.

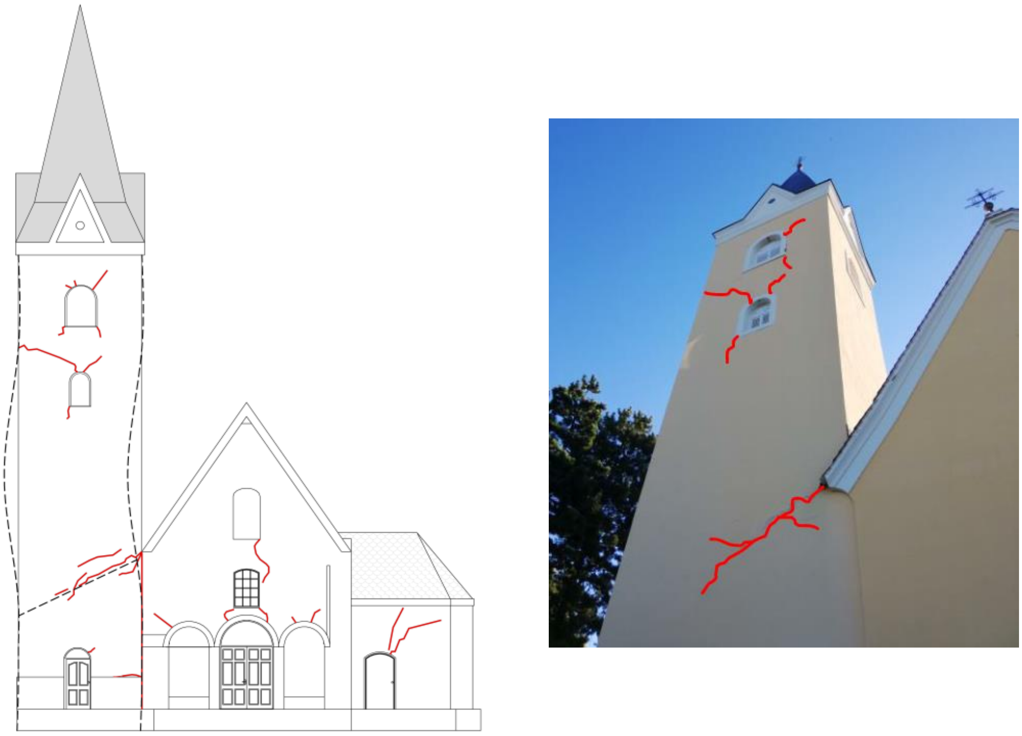


Figure 5. The main failure mechanism of the tower

Other main structural elements, such as walls and vaults, suffered damage characteristic of cyclic seismic excitation. Cracks on vaults occurred on the intrados when the tensile strength of masonry was reached, leading to the formation of plastic joints - hinges, while the walls were damaged mainly at the corners of the openings, i.e. at the points with the highest stress concentration. Timber roof structures were almost not damaged during the earthquake mostly due to their low mass.

2.2.2 St. Mary's chapel, Mala Gorica

St. Mary's chapel in Mala Gorica sustained very severe damage of the tower (level 4 in EMS-98). The combined shear and tension failure of the tower columns resulted in horizontal deflection of the tower in the range of 10 cm at the top, Figure 6. The triumphal arch was also severely damaged and exhibited wide cracks on the intrados and at the crown of the arch, characteristic for cyclic seismic excitation. Ground slab deflections were noted, indicating possible liquefaction of the soil.

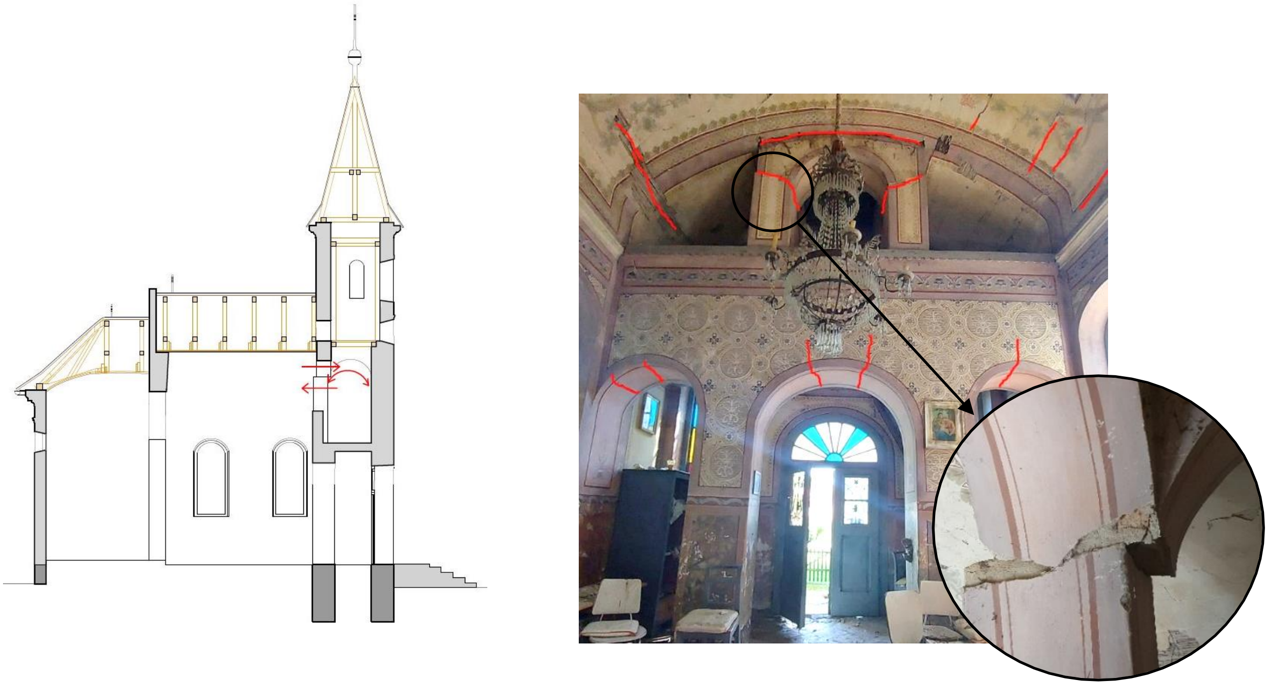


Figure 6. The main failure mechanism of the tower

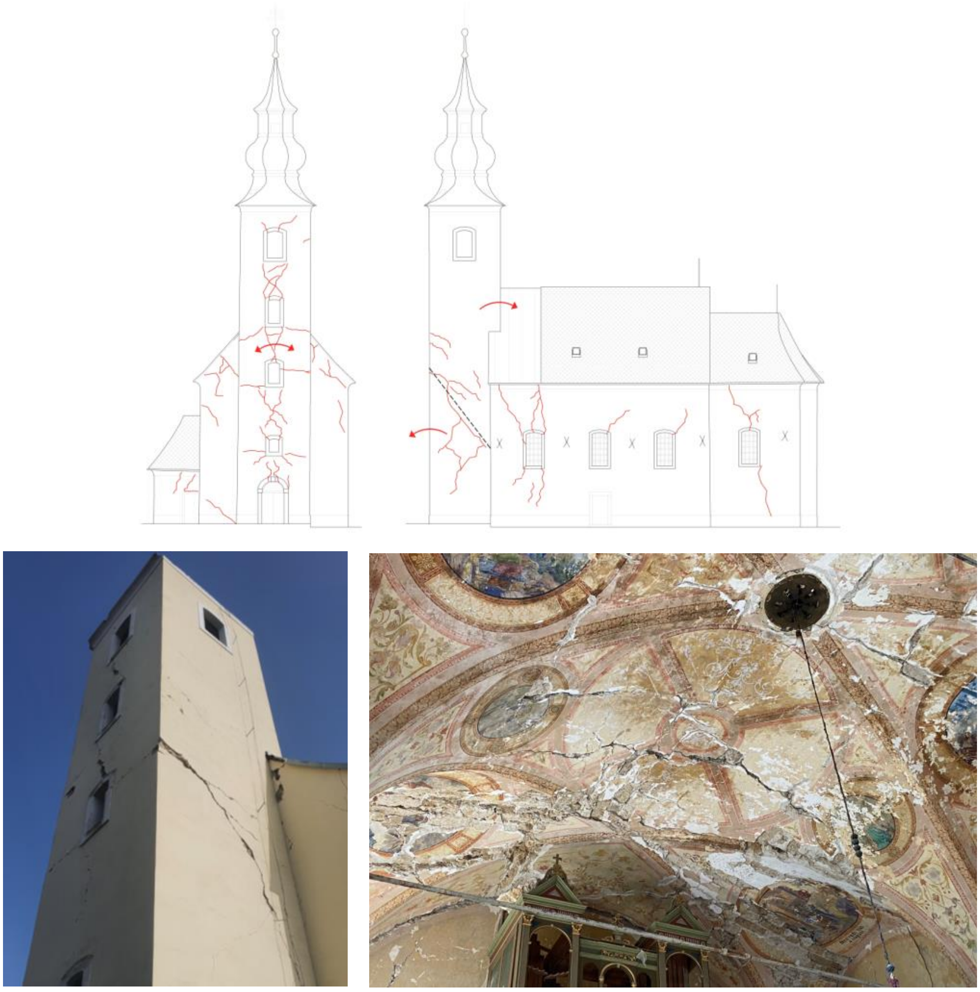


Figure 7. Main failure mechanism of the tower (left) and vaults (right)

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.97

Since the vault of the chapel is a timber barrel vault suspended from a timber roof structure, it was only slightly damaged in the earthquake – the transverse cracks, seen in figure 6, are merely surface cracks in the plaster.

2.2.3 St. George's church, Mala Gorica

On the northwestern façade of the tower, it is easy to distinguish two structural elements - vertical elements around the openings - piers connected with horizontal elements below/above the openings - spandrels. The damage pattern is shown in Figure 7. It refers to the extremely rigid spandrels that suffered shear failure. Diagonal cracks on the side walls form a clear sliding plane. Due to the very severe structural damage - level 4 on the EMS-98 scale - the upper half of the tower was dismantled as an urgent measure. The stone cross-vaults were significantly damaged by tensile failure on both the intrados and extrados. The walls, which were also of stone masonry, exhibited a number of cracks due to shear failure, out-of-plane bending failure (i.e. gable walls in the roof) and failure of the foundation soil. In this case, the timber roof structure was also affected by the earthquake – the failure of the gable walls caused mechanical damage to the timber columns and beams. In addition, the cyclic nature of an earthquake caused localized failure of timber connections, which is to be expected due to the low ductility of traditional carpentry connections.

2.3 Detailed investigation

Destructive, semi-destructive and/or non-destructive testing was performed. Destructive testing consisted of wall, floor and ceiling investigative probes and core drilling of walls. Semi-destructive testing was conducted on the timber structures of the building to determine density and moisture content. Non-destructive testing consisted of thermography and geotechnical investigative works. Thermography results were indicating elevated moisture content in the assessed structures, mainly in the Church of St. George in Mala Gorica. Increased moisture curing is proposed based on the assessment. One of the most important aspects of evaluating an existing structure is to gather all the necessary information crucial for the global stability of the structure. In the case of sacred structures, these include the geometry, wall thicknesses, wall structure in cross-section [9], foundation depth and soil type [10]. The existence and position of iron or steel ties, the condition of the roof structure is determined by visual inspection and are equally important for predicting the mechanical characteristics of the old masonry walls [11].

3. Structural Analysis of existing church in Gračani

The Church in Gračani is selected for further analysis and retrofit presenting as the only one where retrofitting works have already been executed. Numerical modelling and analysis were carried out in the Abaqus Standard software package [12] for academic purpose of writing this paper. The calculation is based on the finite element method and a dynamic nonlinear analysis of the structure was performed. The action of an earthquake was simulated with the acceleration of the ground at the location approximately corresponding to the earthquake that shook Zagreb on March 22, 2020. The frequency spectrum of the ground motion record corresponds to the currently valid regulation in the Republic of Croatia. The earthquake is defined by two horizontal and one vertical component. Due to the geometry and complexity of the model, volumetric finite elements were used. In addition, the Concrete Damage Plasticity (CDP) model was used to simulate the masonry wall behaviour. The CDP model of masonry assumes two types of failure mechanisms, namely tensile cracking and compression crushing of the material. In compression, the relationship between stress and strain is linear up to a certain point, followed by hardening to maximum stress and subsequent softening of the material with inelastic deformations. For tensile stresses, the model follows a linear relationship until a crack appears in the material. After that, softening occurs with the localised deformations in the element. The behaviour of masonry in the cracked state implies the definition of the post-critical stress as a function that depends on the crack tensile deformations. Due to the problem of excessive sensitivity of the mesh in materials with extremely unstable post-critical behaviour, the behaviour of the material in tension is described by the fracture energy criterion, which represents the energy required to open a unit area of the crack and is a property of the material. In addition to the described behaviour in tension and compression, the function of the yield surface is additionally defined, which takes into account the triaxial stress state. The finite element mesh is formed by tetrahedrons and hexahedra of approximately equal size and regular shape and is coordinated with the behaviour of the material in the post-critical tensile region where the system is unstable and sensitive to mesh selection.

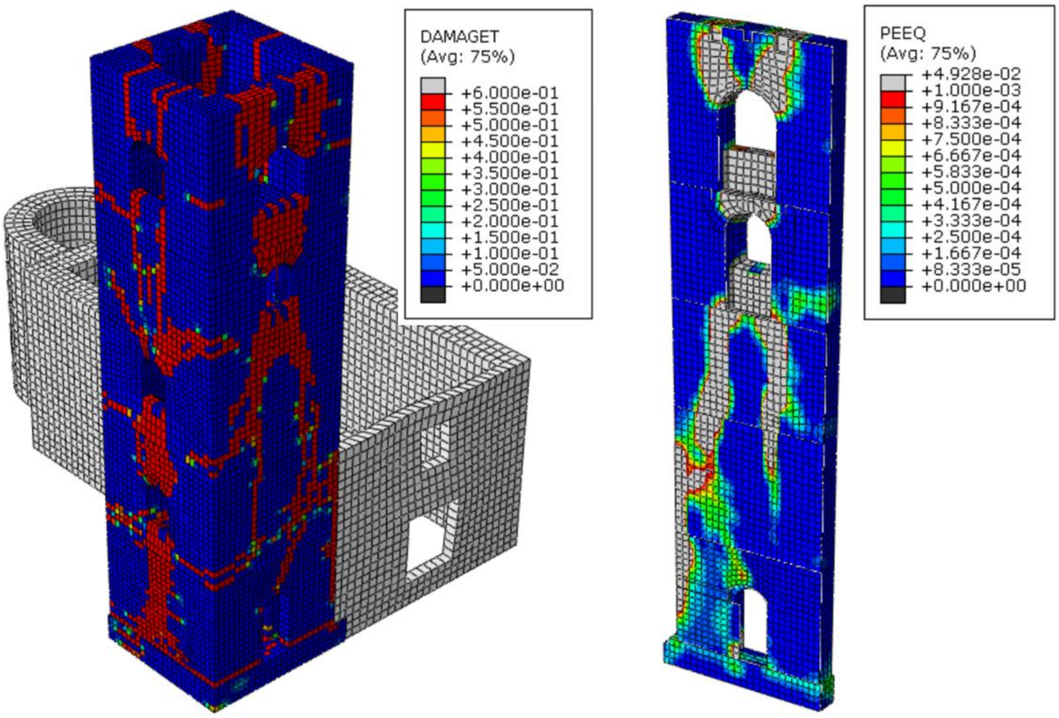


Figure 8. Bell tower damage distribution due to tensile stresses (a) and crack propagation area in the front wall (section through the front wall shown) (b) – existing condition

It can be seen that the numerical model complements relatively well with the cracks that appeared on the bell tower and the vault of the church, Figures 8, 9 & 10. It should be emphasized that a large part of the cracks in the structure is not visible due to the facade or because they are inside the wall. Areas of material damage (material crushing and tensile cracking) on the top of the church vault are more difficult to see visually because of the layers of the vault on the upper side. However, such damage is dangerous because it represents crack propagation sites even under dead load. Vaults are slender and very sensitive to any dynamic and horizontal influences.

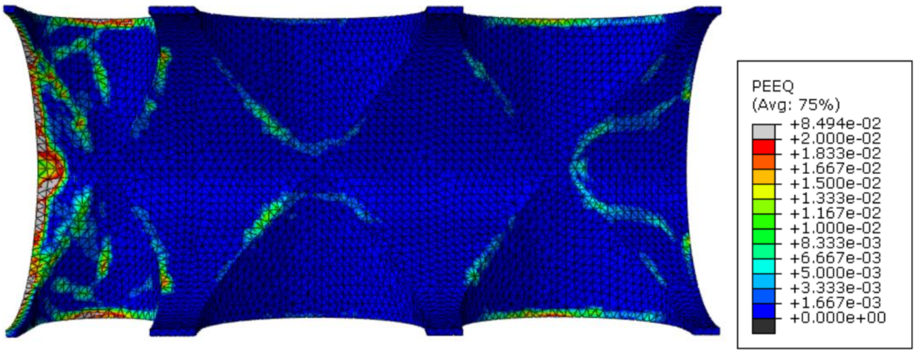


Figure 9. Area of propagation of cracks on the inside of the church vault shown through equivalent plastic deformations

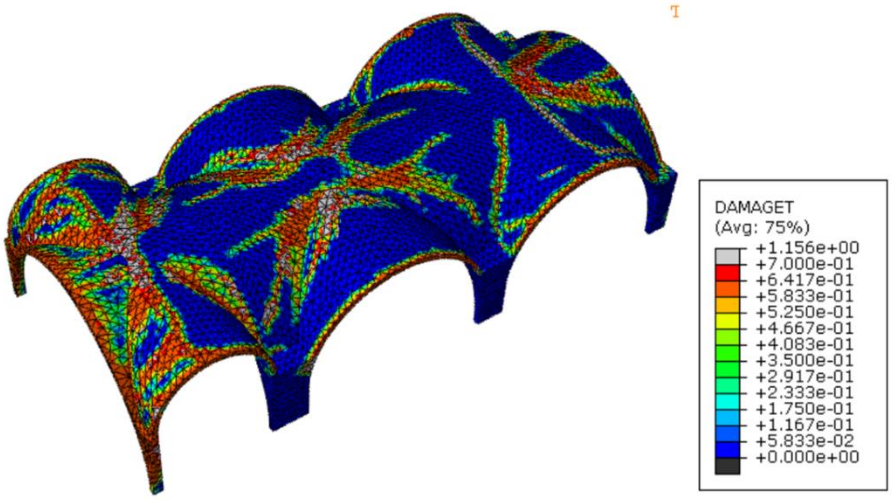


Figure 10. Propagation of material damage in the vault due to tensile stresses

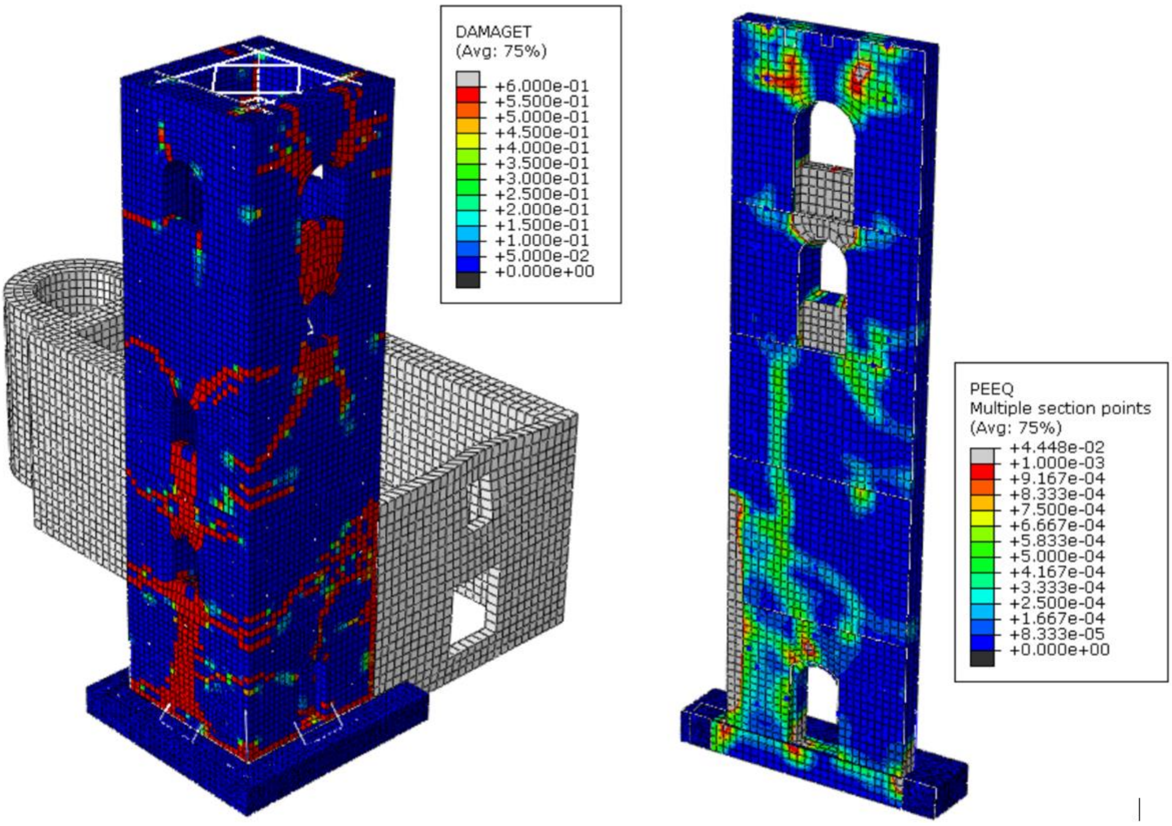


Figure 11. Bell tower damage distribution due to tensile stresses (a) and crack propagation area in the front wall (section through the front wall shown) (b) – reinforced condition

The calculation was also performed for the retrofitted model of the structure. The result of plastic deformation and damage of the tower is shown in Figure 11. There are still areas where cracks occur and propagate. However, this area is clearly localized and confined. Based on the amplitude of the plastic deformations, it can also be seen that they are much smaller and narrower. The area of damage is similar even after the strengthening of the tower, affecting similar critical elements dominated by microcracks of limited width, since thanks to the reinforcing elements, the stress is redistributed within the material, preventing the collapse of the wall or the lintel. Critical elements are the parts between the

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.2023.97

openings (arches and parapets), which are an integral part of the structure, but do not take over the dominant permanent load or the earthquake load. Therefore, it is important to preserve their integrity during an earthquake.

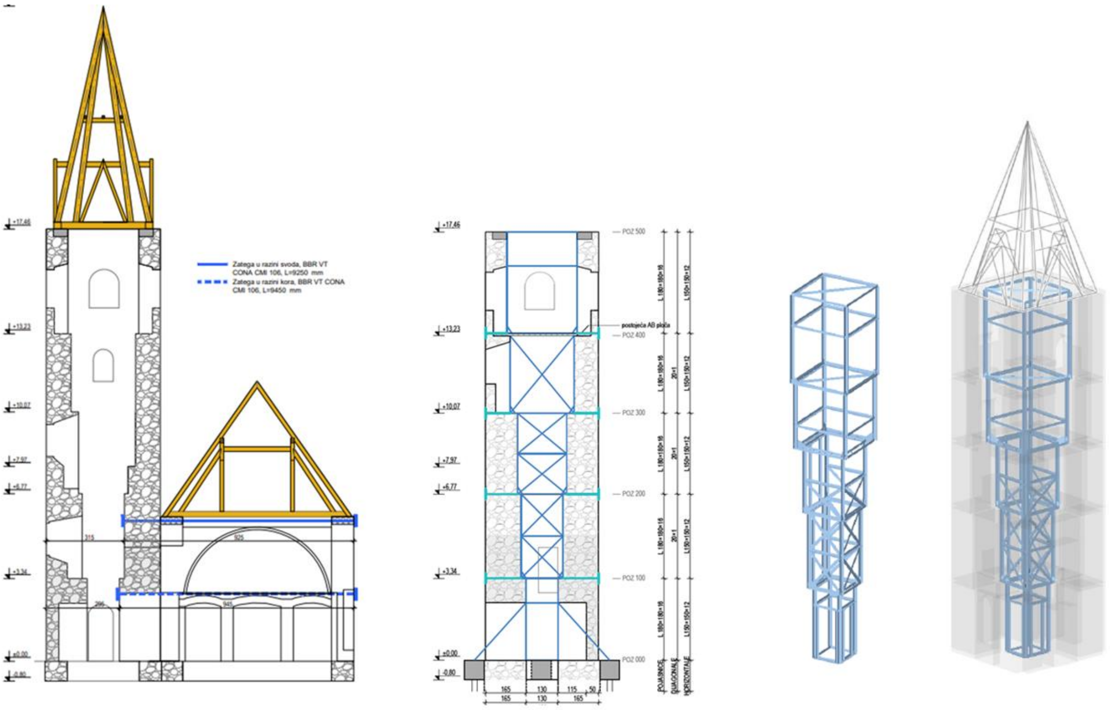
4. Retrofitting Techniques and Strengthening Materials

4.1 Bell tower

The strengthening of the bell tower due to a shear failure at the level of the church cornice is conceptually predicted by the interpolation of a new shear resistant structure along the inner side of the bell tower walls. Considering its importance for the global stability of the entire structure, the proposed concept can be implemented in two ways: with an interpolated steel grid discretely connected with anchors to the basic masonry structure or with a reinforced concrete insert in the form of unilaterally concreted wall adjacent to the inner wall at the critical height of the bell tower. The steel option is extremely complex to install, but it is a reversible design that does not significantly compromise the original stiffness of the historic structure, Figure 12. However, in conjunction with external horizontal clamps and stainless steel connection anchors, this steel structure upgrades the earthquake resistance capacity and prevents a whole range of premature local out-of-plane wall failures. The steel structure partially takes over the tensile component of the global bending resistance of the bell tower as a cantilever with steel tensile flanges at the corners of the bell tower. In principle, the reinforced concrete version is easier to implement than the steel version. However, this design has a significant effect on the global behaviour of the masonry tower, as new critical zones are created at the transitions between the reinforced and unreinforced segments. It is also important to note that this is an irreversible type of strengthening that irrevocably removes some of the historic value of the structure. Both options provide for strengthening of the foundation in the form of a grid of foundation strips, which are additionally anchored by vertical geotechnical anchors.

4.2 Vaults

Although the existing horizontal confinement concrete member along the perimeter of the church walls contributed significantly to the good behaviour of the structure during the earthquake, the cracks detected indicate the beginning of the opening of the damage mechanisms of the vault.



DOI: https://doi.org/10.5592/CO/2CroCEE.2023.97

Figure 12. Chosen strengthening method for the tower

Slight separation of the longitudinal walls from the vault, leaves it in an unstable semi-restrained state, which can progressively result in partial collapse during stronger earthquakes. Therefore, both as a repair and strengthening measure, two groups of procedures are carried out, that would significantly increase the resistance of this masonry structure. As a stabilization measure, a system of orthogonal post-tensioned ties are installed in both main directions at the level of the top of the vaults. This reduces the possibility of detachment of the main support lines.

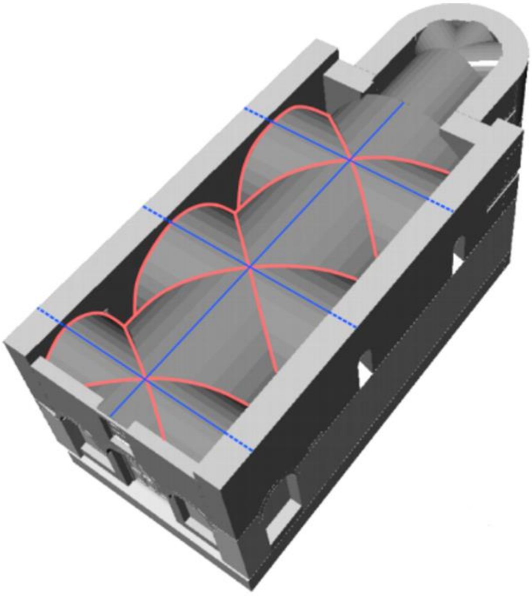


Figure 13. Strengthening of the masonry vaults (red line – uniaxial carbon fiber fabric, blue line – post tensioned steel ties)

The second strengthening method is linear strengthening of cross-sectional joists of cross vaults using carbon fiber fabric aligned in the direction of the joists, Figure 13. Both methods are reversible techniques that interfere minimally with the basic structure and can be performed effectively where monitoring and regular maintenance are performed.

4.3 Stone wall

Due to the poor stone structure of the masonry walls of the bell tower, as determined by investigative probes and endoscopic examinations of investigative boreholes through the body of the walls, measures are foreseen to connect the outer leaves of the walls with stainless steel rods. Grouting is also planned for the lower part of the tower walls with natural lime-based grout. Transverse connecting of two leaves of the walls is proposed via inox steel bars spaced in a 100 x 100 cm grid. It is important to not that inox steel bars must be installed and pretensioned before the grouting. Following the heritage guidelines (ICOMOS [13]), the retrofit techniques include materials that are sustainable and durable, such as Inox steel bars and hot-dip galvanized steel elements. All these materials are highly resistant to the atmosphere. The materials and products used improve the mechanical characteristics, ductility and durability of an existing structure.

5. Conclusion

Finally, safety requirements should also be mentioned, as they represent an inevitable challenge in the high-quality rehabilitation of historic structures. According to the regulations in force for the church of St. Michael, a complete renovation of the building is foreseen, with seismic action calculated for a return period of 225 years. At the same time, the rehabilitation project comply with the special conditions for the protection and preservation of cultural assets. Thus, according to the current

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.2023.97

regulations, the designer must provide technical solutions that ensure the safety of people and preserve the authenticity of the architectural heritage, which is often a challenge. Often, the rehabilitation of the architectural heritage is seen as something permanent and regular maintenance, which is crucial for a longer service life of the structure, is often omitted. A holistic approach to architectural heritage rehabilitation is certainly the best guide for the future. Following the ICOMOS principles for analysis, preservation and retrofitting and using materials and products that are durable and reversible, the long-lasting and easily replaceable strengthening elements should be integrated into the existing structure in a way that ensures their preservation for future generations.

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] The Database of Usability Classification, Croatian Centre of Earthquake Engineering (HCPI - Hrvatski Centar Za Potresno Inženjerstvo), Faculty of Civil Engineering, University of Zagreb and The City of Zagreb, June 2020.

[3] 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.

[4] Commission, U. S. S. All About Earthquakes: The Science Behind Earthquakes. All About Earthquakes: The Science Behind Earthquakes. Natural History, Museum of Utah, University of Utah: Salt Lake City 2010, p 1.

[5] World Bank Report: Croatia December 2020 Earthquake – Rapid Damage And Needs Assessment, 2020, March 2021, Government of Croatia.

[6] Comisión Sismológica Europea. Escala Macro Sísmica Europea EMS - 98; 1998; Vol. 15.

[7] Law on Reconstruction of Earthquake-Damaged Buildings in the City of Zagreb, Krapina-Zagorje County, Zagreb County, Sisak-Moslavina County and Karlovac County (NN 102/2020, 10/21).

[8] Tehnički Propis o Izmjeni i Dopunama Tehničkog Propisa Za Građevinske Konstrukcije [Internet]. [Cited 2021 Jun 29]. Available from: Https://Narodne-Novine.Nn.Hr/Clanci/Sluzbeni/2020_07_75_1448.Html.

[9] Ortega, J.; Vasconcelos, G.; Rodrigues, H.; Correia, M. Seismic Vulnerability and Loss Assessment of Vila Real de Santo António, Portugal: Application of a Novel Method. Int. J. Archit. Herit. 2020. https://doi.org/10.1080/15583058.2019.1709915.

[10] Cianchino, G.; Masciotta, M. G.; Verazzo, C.; Brando, G. An Overview of the Historical Retrofitting Interventions on Churches in Central Italy. Appl. Sci. 2023, 13 (1). https://doi.org/10.3390/APP13010040.

[11] Borri, A.; Corradi, M.; Castori, G.; De Maria, A. A Method for the Analysis and Classification of Historic Masonry. Bull. Earthq. Eng. 2015, 13 (9), 2647–2665. https://doi.org/10.1007/s10518-015-9731-4.

[12] https://www.3ds.com/products-services/simulia/products/abaqus/abaqusc ae/.

[13] Lourenço, P. B. The ICOMOS Methodology for Conservation of Cultural Heritage Buildings: Concepts, Research and Application to Case Studies; 2014. https://doi.org/10.14575/gl/rehab2014/095.