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Architectural Study and Preliminary Seismic Assessment of a Typical Unreinforced Brick Masonry Building in Zagreb, Croatia

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Abstract: This paper presents a case study of an unreinforced masonry building in central Zagreb, which sustained moderate damage during the 2020 earthquakes. Situated within the Lenuci Horseshoe—a planned urban and landscaped space integral to Zagreb's historic Lower Town—the building is part of a significant urban achievement, reflecting the city's development from the late 19th to the early 20th century. The study explores the architectural and historical context of the building, its design features, and its role within Zagreb's broader urban and cultural heritage, highlighting its value as a case study in balancing preservation and functional reuse. A multidisciplinary approach, including architectural documentation, archival research, laser scanning, damage analysis, and nonlinear modeling using 3Muri software, was employed to comprehensively assess its seismic behavior. Furthermore, the study examines retrofitting strategies that harmonize structural safety with cultural heritage preservation within the Croatian context.

Keywords: URM; earthquake; heritage; seismic; shotcrete; renovation; Zagreb

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1. Introduction

Masonry structures have been extensively used throughout history, especially in Europe. In Croatia, unreinforced masonry (URM) constitutes a significant portion of the building stock, particularly in historic urban areas. However, the seismic vulnerability of these structures presents a substantial challenge, as was evident during the recent Croatian earthquakes in 2020 [1] and other recent earthquakes in the Mediterranean [2–5]. In the recent Kahramanmaraş earthquakes in Türkiye, this vulnerability was further demonstrated, as extensive structural damage was observed in adobe buildings and masonry educational facilities [6,7].

On 22 March 2020, Zagreb was struck by an earthquake of magnitude M_L = 5.5. The earthquake caused considerable damage, particularly in the historic Lower and Upper Town areas, where many buildings are constructed of URM. A subsequent earthquake on 29 December 2020, with an epicenter near the town of Petrinja (approx. 50 km from Zagreb) with a magnitude of M_L = 6.3, further impacted the region. The Zagreb and Petrinja earthquakes caused significant destruction, with the total damage estimated to be around EUR 19.9 billion. The Croatian Center for Earthquake Engineering reported that over 82,000 buildings suffered damage due to the seismic activity. More information about these two earthquakes can be found in recently published articles [8–10] and reports issued by the World Bank [11,12]. These earthquakes not only resulted in substantial financial losses but also impacted housing on a large scale, including many heritage-protected structures that were either significantly harmed or completely destroyed. Figure 1 shows a rapid

post-earthquake assessment of one building block in Zagreb, with explanations of the colors in Table 1. Figure 2 shows two photos of typically damaged URM buildings in affected regions.

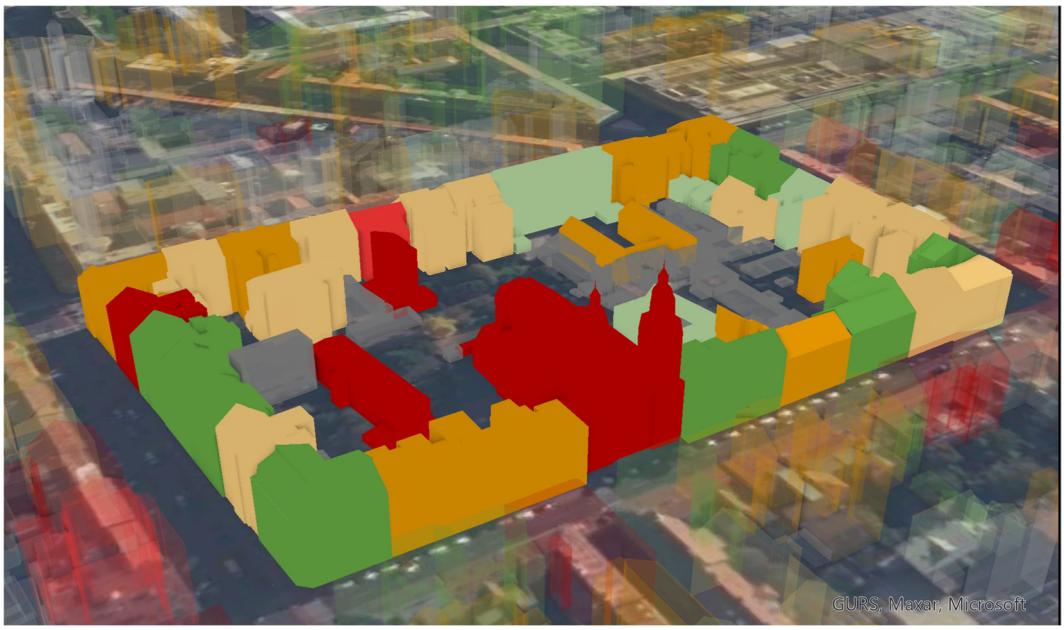


Figure 1. Rapid post–earthquake assessment results in terms of usability of existing buildings.

Table 1. Post-earthquake usability assessment labels [10].

Label	Legend	Description
U1		Usable without limitations
U2		Usable with recommendations
PN1		Temporarily unusable—detailed inspection needed
PN2		Temporarily unusable—emergency interventions needed
N1		Unusable due to external impact
N2		Unusable due to damage



Figure 2. Typical damage to URM buildings in Zagreb.

In the aftermath of these events, numerous buildings were either damaged or rendered unusable, necessitating extensive reconstruction efforts. The challenges associated with

assessing and retrofitting these buildings are compounded by their age and construction methods. Many URM buildings in the affected regions were constructed in the late 19th or early 20th century with construction techniques from Vienna and Budapest, where seismic activity is not a significant concern. The buildings were built with solid clay bricks and lime mortar, materials known for their poor seismic performance. The lack of confining elements, such as reinforced concrete (RC) beams and columns, further exacerbates their vulnerability, leading to common failure modes, such as in-plane shear failure, out-of-plane collapse, and partial or full gable wall collapses. Figure 3 shows a typical building in the Lower Town of Zagreb from the eve of the 20th century.



Figure 3. Typical URM Zagreb buildings in the beginning of the 20th century.

In Croatia, legislative measures have been enacted to address the reconstruction of earthquake-damaged buildings. The Law on Reconstruction of Earthquake-Damaged Buildings [13], updated following the 2020 earthquakes, outlines the levels of reconstruction required to meet current seismic standards. However, the implementation of these regulations has faced challenges, particularly regarding the timely and effective execution of reconstruction projects, especially when renovating listed buildings. The seismic assessment and retrofitting of existing masonry structures, especially those with cultural and historical significance, remain a priority. Preserving cultural and historical heritage is a need, as these structures embody the values and identity of societies. Recent advances in retrofitting have focused on strengthening methods that retain the original appearance and design. For example, less invasive techniques, like textile-reinforced mortar (TRM) and fiber-reinforced polymers (FRPs), are being promoted to improve seismic resilience while preserving architectural authenticity [14,15]. However, these methods may not always satisfy stringent seismic standards, such as those set by the current standard (HRN EN1998 [16]). In situations where greater structural performance is required, more robust solutions, like concrete shotcrete, are often employed to achieve the necessary strength and stiffness [17]. Although heritage preservation guidelines sometimes limit the use of such

interventions, in Croatia, concrete shotcrete has been considered acceptable in many cases, balancing both safety needs and heritage conservation objectives.

This paper focuses on the seismic assessment and strengthening of a URM building not so heavily damaged during the 2020 earthquakes located in the heritage protected zone of the city center of Zagreb. The case study illustrates the full assessment phase and proposes strengthening methods for such a building, emphasizing the need for a balanced approach that considers both structural safety and the preservation of cultural heritage. The focus was placed on architectural documentation and the collection of archival data to enhance the understanding of this unique building. Subsequently, several photographs are shown where light damage to the massive structure is presented. The shown damages served as a basis for the validation of nonlinear modeling. The damages were analyzed, and the geometrical features influencing seismic behavior were examined. The Law on Construction and the Law on Reconstruction [18] were referenced to illustrate the challenges in meeting current seismic standards. The central issue remains the preservation of heritage; during the renovation process, each building, according to the Law on Construction (or 75% of the normative demands if the building is built before 1968), is required to comply with earthquake resistance standards as specified by HRN EN1998, which presents significant difficulties. Further details on Croatian legislation can be found in the following literature [19,20].

The article is organized as follows. Section 2 provides an overview of the architectural background and history of the case study building, followed by an examination of its structural characteristics, including floor plans and cross-sectional views. Section 3 shows the damage sustained during the 2020 earthquakes, along with the investigative work to identify the building's geometry, the mechanical properties of the material, and construction details. Nonlinear models in 3Muri software Version 14 [21] are presented. Section 4 discusses the analysis results and proposes recommendations for structural strengthening. Finally, the conclusion highlights the key challenges of renovating existing URM structures in Croatia, using this case study to illustrate these points.

2. Case Study

2.1. Architectural Background

The building is located at Antuna, Ivana, and Vladimira Mažuranića Square (house number 20) and is part of a protected historical area, although it is not individually designated as protected cultural property. The building was designed by Vjekoslav Bastl, one of the prominent figures in the architectural scene in Zagreb and Croatia at the beginning of the 20th century. The building in question is one of his later works, created during the neo-classicism phase of his architectural career. Figures 4 and 5 show the case study building and the surrounding square.

The case study building is part of the protected Lenuci Horseshoe shown in Figure 6. The "Green Horseshoe" or "Lenuci Horseshoe" is an integral part of the Lower Town (Donji grad) of Zagreb, developed as a planned and urbanistically defined space from the first Regulatory Plan of the City of Zagreb in 1865 until the late 1920s. It consists of a sequence of eight squares in the Lower Town. It is the most significant urban achievement and an original accomplishment in city planning. As a completed urban, architectural, and landscaped space in the central zone of Zagreb, it documents a crucial period in the city's development. The Green Horseshoe was conceived as a unified entity in the 19th century, with development continuing into the 20th century, and it is attributed to Cirilo Jeglič and Milan Lenuci.



Figure 4. Aerial view of the case study building and the surrounding square.



Figure 5. Aerial view of the case study building (left) and the surrounding square.



Figure 6. The "Green Horseshoe" and the location of the case study building.

The architectural concept for the building was created in 1913. Construction progressed rapidly, and, by early 1914, the building was already roofed, as shown in a photograph published in January 1914 (Figure 7). The purpose of the building was to house the "Kraljevski sveučilišni ludžbeni zavod" or the Department (Laboratory) for Chemistry. Just two years later, Bastl designed another building to the west, known as the Institute for Physics (Figure 7—right building).

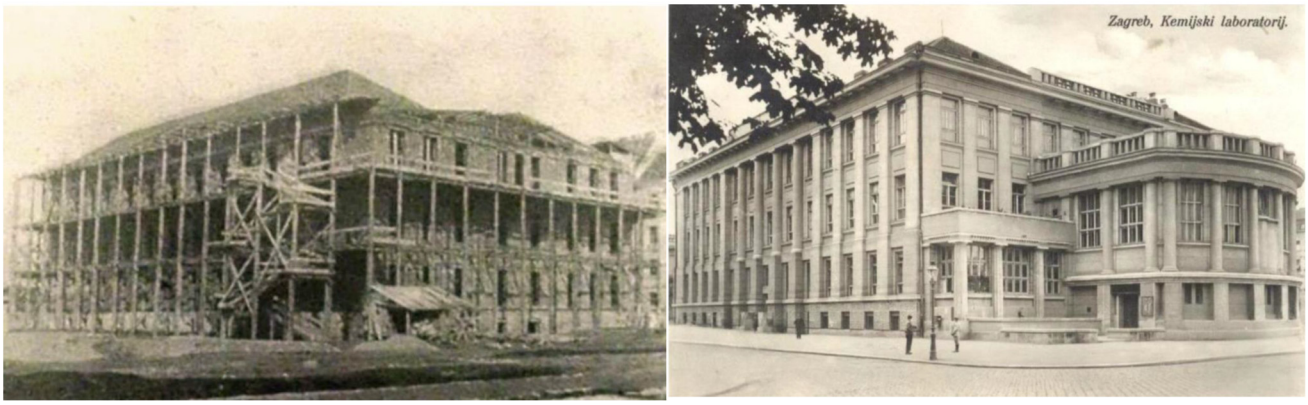


Figure 7. Two photos of the building complex: during construction in 1914 (left) and a photo of the finished building taken in the period between 1918 and 1927.

The main body of the building has a rectangular plan (Figure 8) and a structure consisting of a basement, a ground floor, two floors, and an attic (Figure 9). It is clearly defined and articulated externally by vertical lines of rectangular, minimally decorated pilasters and Doric half-columns in the central part of its main facade. Simplified and geometrically reduced moldings are found on the dividing cornices and the main cornice that runs around the building.

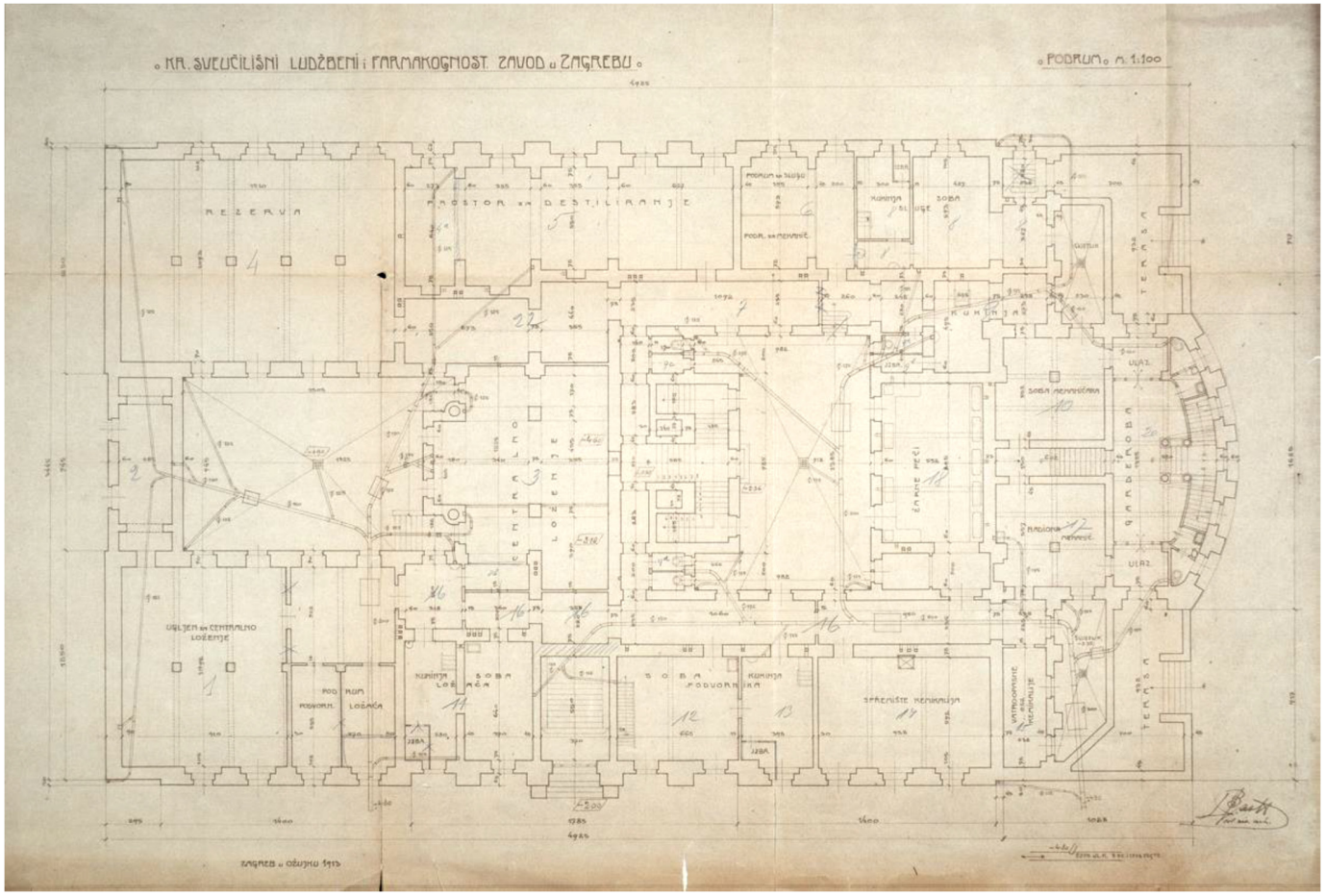


Figure 8. Original drawings of the floor plan.



Figure 9. Original drawings of the south and north facades.

Attached to the main structure is a smaller section, both in width and height (up to the ground floor and the first floor of the main building), which housed the main lecture hall, the "amphitheater", and accompanying spaces (lobby, restrooms on the ground floor). This smaller, more elaborately decorated structure disrupts the relatively regular rectangular disposition of the rest of the building's main body. Figure 8 shows the original drawing of the floor plan found in the State Archives.

Internally, the spatial structure was defined by a clear division into two sections (north and south) connected by a central corridor on each floor, along which a multi-flight representative staircase was organized. The central staircase was flanked by two pairs of representative columns that were fluted in the basement and on the first floor, without capitals, while, on the second floor, their upper ends were defined by Ionic capitals. The walls around the staircase featured discreet, profiled decorations (regular orthogonal fields and shallow niches without significant moldings or similar decorative elements). The most notable decoration along the edges of the ceilings consisted of decorative consoles found on all representative floors.

The basement and the third floor (attic) initially contained utilitarian rooms, storage areas, and a boiler room in the basement, as well as the caretaker's apartment in the attic. The building's interior was opened up with two inner courtyards arranged along the longitudinal axis, each with a strictly utilitarian function. The facades of these courtyards were not decorated, and most of the spaces adjacent to them were circulation areas or restrooms, which had views, light, and ventilation from them. Today, this space has retained its utilitarian function, with numerous ventilation installations and shafts arranged in these atriums (especially in the southern one), as well as two small outbuildings (sheds/stores), with a larger one in the southern courtyard and a smaller one in the northern courtyard. Classrooms and other teaching spaces were formed along the building's facades and along the two longitudinal corridors, with several also located along the inner courtyards and adjacent to the staircase area. The northern facade of the building is rich in decorative elements, which exhibit a much higher level of detail and ornamentation, representing a significant departure from the rest of the building's main body. The neoclassical elements of the Doric order continue to vary on the northern facade, with the use of higher-quality materials and more elaborate profiling than throughout the rest of the building. The lower zones are also treated with a higher-quality decorative stucco finish, which is hand-crafted, with an artificial stone texture that differs significantly from the zones on the eastern, southern, and western facades.

A significant brick chimney, which extended from the basement to above the roof of the staircase wing, was located in the southern atrium until the Zagreb and Petrinja earthquakes. After the earthquakes, it was completely removed.

During the building's use, only minor alterations were made to the layouts of individual spaces, with most of the laboratories preserving their historical spatial integrity. The most significant changes were made to the utility spaces, such as restrooms, which were modernized on all floors, and to ventilation and other safety systems in the chemical and biological laboratories, which are visible on the interior facades of both atriums. On these facades, besides ventilation shafts and ventilation motors, numerous installations of modern split air conditioning units are visible, with external units placed freely and randomly on these facades.

Among the most significant structural and nonstructural changes to the original layout of the building's structure are the following:

- The removal of the traditional gabled wooden roof above the central staircase and the addition of a new floor (currently mostly occupied by a library) with the flat roof above.
- The partial rearrangement of the attic for office and laboratory use, with the raising of part of the parapet wall along the southern atrium to allow for the addition of windows and changes in the roof's geometry.
- The installation of numerous skylights, especially on the roof above the southern facade, where parts of the roof feature a series of windows installed in improvised dormer structures.

- The installation of mechanical ventilation systems for various laboratories (separate units and sections) on the flat roof above the staircase section, and their modernization over time.

2.2. Rapid Post-Earthquake Assessment and Preliminary Analysis of the Existing Structure

After the earthquake, the building was labeled Temporarily Unusable, and the damage was assessed according to the EMS-98 [22]. In accordance with the identified damage, the building was classified as Damage Grade III (D3)—significant to severe damage, characterized by moderate structural damage and severe nonstructural damage (primarily due to the separation of the stairwell wall). Later, the assessment was revised to a level between D1 and D2. The basic conclusions were that the building sustained minor damage, primarily to brick masonry walls, with the most significant damage observed around the lintels of openings. Some of the damages are shown in Figure 10, and they are divided into three groups: (a) damage caused by shear force at the contact of two different types of materials, poorly connected and carried out over the years through conversion of space and building maintenance, (b) damage caused by the opening of a diagonal crack that passes through vertical and horizontal mortar ties, caused by shear forces, and (c) damage caused by the opening of vertical and horizontal cracks above larger openings, cracks that pass through the mortar ties and some brick elements, and cracks caused by a combination of bending moment and shear force. A comprehensive damage survey was conducted, and all damages were mapped by number and location using both 2D and 3D models (Figures 11 and 12). The procedure was performed for every floor; here, just ground floor mapping is shown.



Figure 10. *Cont.*



Figure 10. Damages to the case study building: most of the damage was caused by sliding along the mortar joints, as well as the opening of diagonal cracks (red arrows show crack lines).

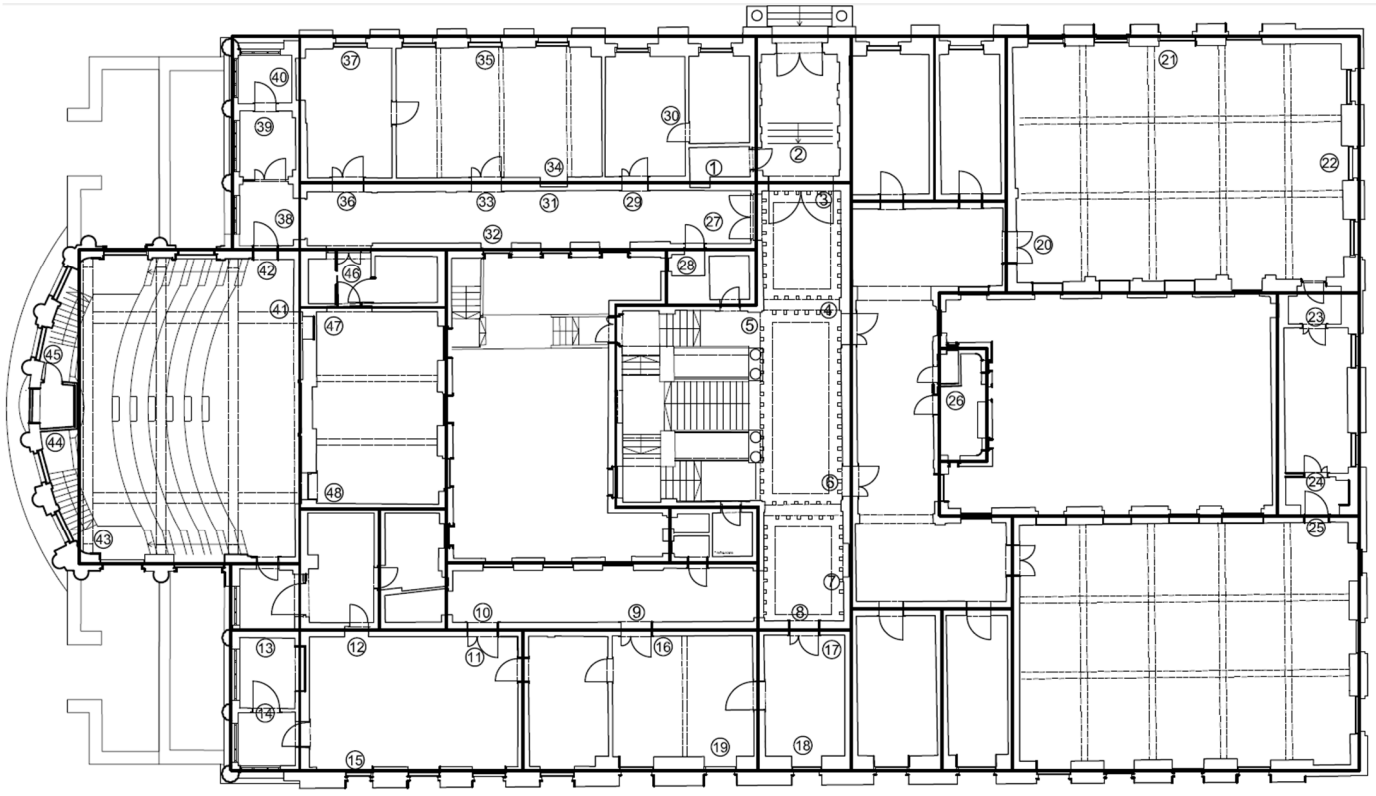


Figure 11. Distribution of damage across the building's ground floor, with damaged areas labeled with numbers for better explanation to the building owner.

The basic conclusions of preliminary reports were that renovation should include both the repair and strengthening of the structure. This involves first connecting the structural elements and assemblies of the building to each other. The renovation approach should start with urgent measures to repair structural or secondary elements that pose risks to

life and health (such as chimneys and gables, as observed in the Zagreb earthquake) and repairs of the existing damage.

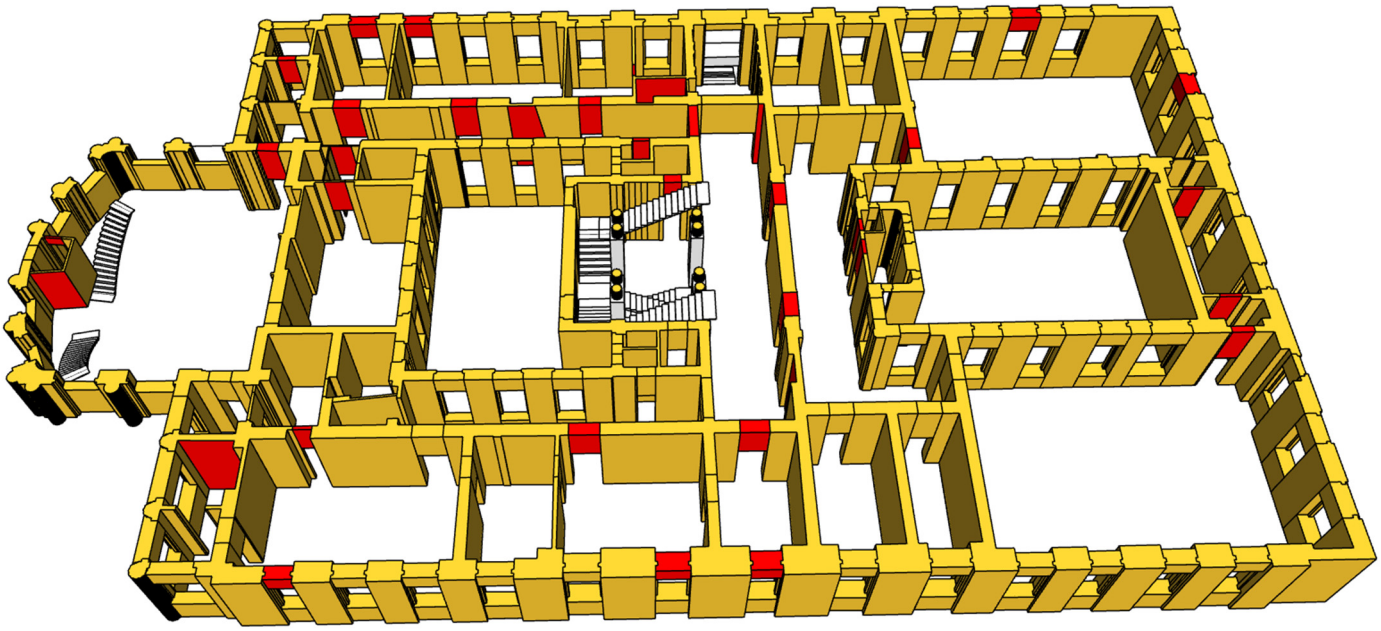


Figure 12. Distribution of damage across the building's ground floor, with damaged areas labeled in red.

3. Architectural and Structural Investigation

3.1. Architectural Survey

To conduct an architectural survey of the complex building, a laser scanning technology was employed to capture the geometry and details of the case study building. The process began by planning the survey carefully, identifying key areas that needed to be documented to ensure comprehensive data capture. The laser scanner Leica BLK360 was used. The scanning was carried out in multiple stages, with each stage requiring approximately 60 to 90 min, including scanning and repositioning on the multiple points of view. The total number of stationary recording points for the whole building was more than 650, so the survey was estimated to take at least 45 h. Following the completion of the architectural survey, the point clouds obtained were prepared for analysis to measure the geometry of the building. The point clouds were imported into Cyclone REGISTER 360 (BLK Edition) software designed for processing three-dimensional survey data, where the point clouds were aligned to create a unified and accurate model of the building's structure. The processing of the point clouds required between 10 and 15 h. Figure 13 is an illustration of the point cloud 3D scan results that combines over twenty separate locations within the building's structure and shows all details related to the scale and proportions of the corridors by the main staircase on the basement, ground, first, and second floors, as well as the addition of the library spaces above the second floor.

Once the model was unified, various geometric measurements could be extracted. Dimensions, angles, and surface areas were measured by analyzing the spatial relationships between points within the point cloud. This detailed analysis enabled the production of precise 2D plans, elevations, and 3D models, which are essential for architectural analysis, renovation planning, or digital archiving purposes. The illustration in Figure 14 clearly shows how the display can be a clear presentation of an orthogonal projection of the point cloud. The illustrations in Figure 15 show detailed views of the space and structure of the main staircase, which is visible on the outer surfaces of the volumes in question. The

illustrations in question enable the monitoring of deformations and damage in realistic positions and with an accuracy of ±3 mm, while in their 3D form they represent a 3D digital imprint of the building itself.



Figure 13. A cross-section in the east–west direction.

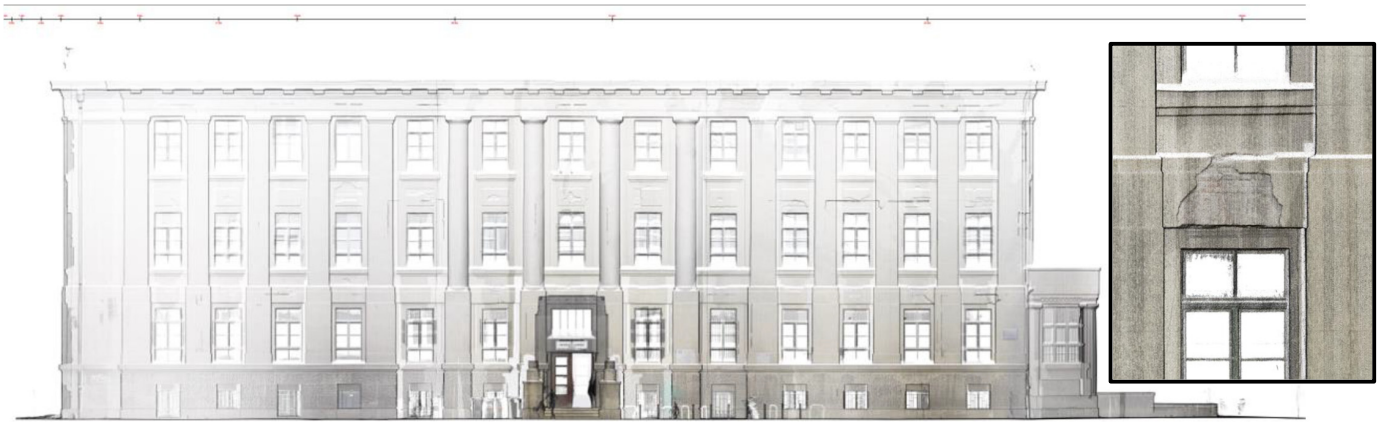


Figure 14. View of the entire eastern facade of the building with details of the damage on the facade surface (displayed in the upper right frame).

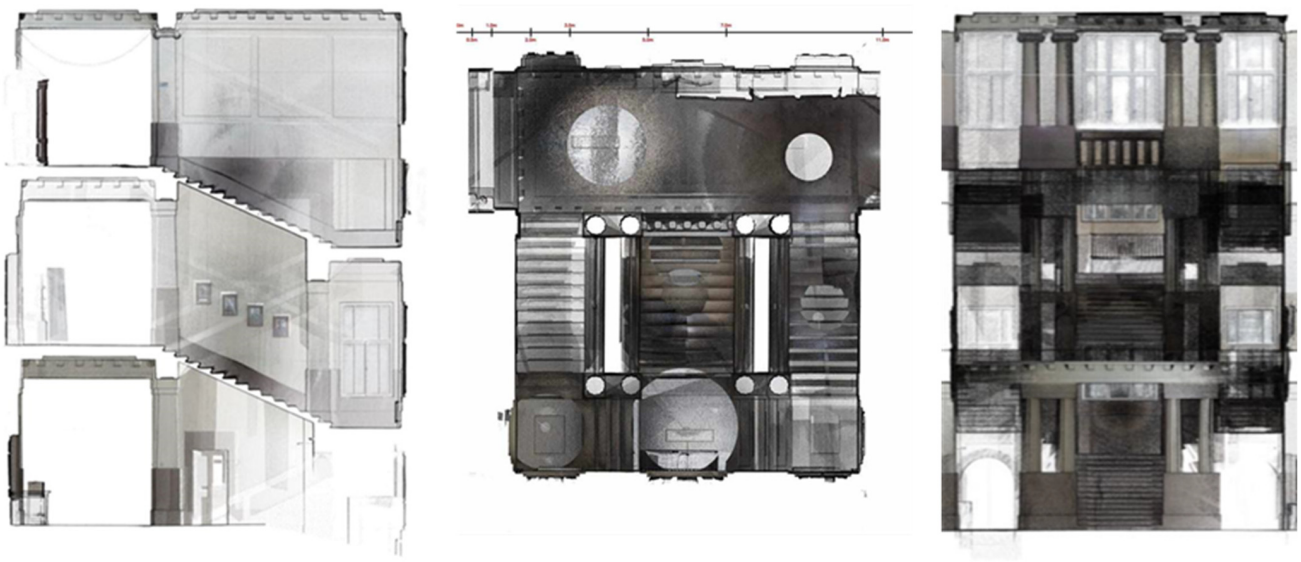


Figure 15. Three detailed basic orthogonal projection (as parts of the illustration that present the section on the left, the floor plan in the middle, and the view of the main staircase area on the right) as a result of spatial data collected in point cloud form (obtained through 3D scanning).

The facades demonstrate less physical damage to the surfaces, but significant damage from graffiti and moisture is evident (both capillary moisture in the lower zones and rainwater across the entire facade, especially on the prominent parts of the capitals or the bases of the half-columns). The eastern facade shows discoloration in some areas (due to the leaching of pigments in the finishing layers of plaster and paint on the facade), as well as fungal and mold growth in others (manifesting as dark spots on the facade surfaces), which represent the most significant form of damage. Parts of the facade on the eastern side are also damaged by peeling (or removed) plaster (down to the brick elements of the load-bearing structure), but, interestingly, no cracks can be observed in the brickwork. Discoloration from rainwater exposure is also visible. The details of the facades on the south, east, and west sides of the building are largely similar, featuring a series of reduced geometric decorative profiles that appear in several horizontal and vertical zones. This is highlighted by the roughly treated base of the building, with a stone plinth that stands out due to its different treatment, profiling under the windows or on the cornice of the building, and the profiling of pilasters that are present on all three facades. Mechanical damage to the facade (with parts of the stucco that have fallen or been chipped away after the earthquake) is visible on both the western and eastern facades, but the damage is more severe on the western side. There are no visible cracks in the masonry parts of the facade structure to any significant extent. Interestingly, more significant damage is only present in the areas of the facade between the pilasters and the half-columns, while it is almost absent on the half-columns and the orthogonal pilasters.

After the laser scanning was completed, the captured data were processed in CAD (Autodesk AutoCad [23]) and point cloud review software (Autodesk ReCap [24]) to detect the basic measurements and to produce precise 2D drawings. The point clouds generated from the scans were analyzed and converted into detailed floor plans, elevations, and cross-sections. The drawings in Figure 16 present characteristic point cloud representations of the multiple laser scans, which served as a basis for defining architectural drawings and other technical matters necessary for the analysis.



Figure 16. Point clouds that served as a basis for defining precise technical drawings.

The resulting 2D drawings provided a layout of the building's geometry and architectural features, as shown in Figure 17. The building has floor plan dimensions of 35 × 61.4 m, with an oval annex to the north.

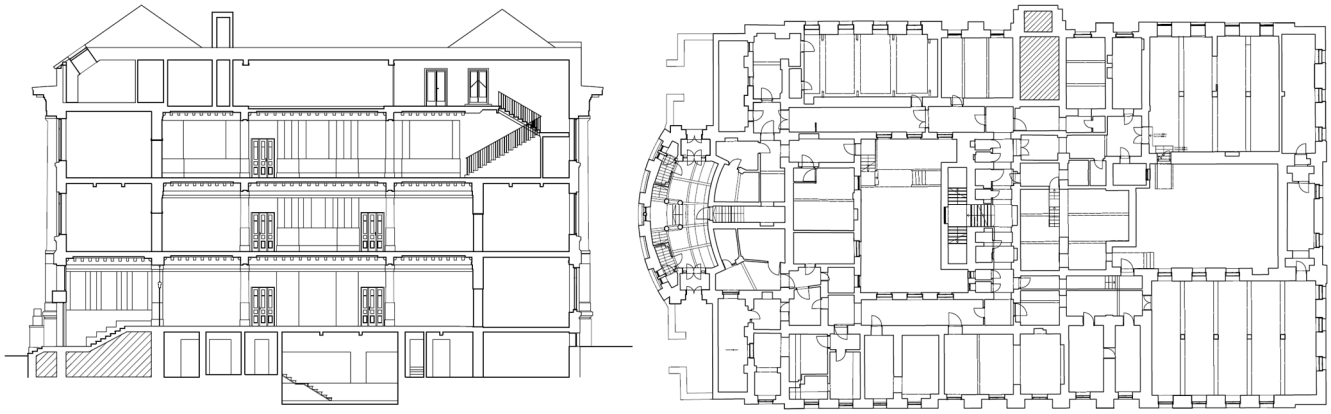


Figure 17. One cross-section of the building and the floor plan of the basement level prepared as technical drawings for further analysis.

The load-bearing walls of the building are constructed from brick masonry typical of the Zagreb region in the late 19th century and the beginning of the 20th century. Clay brick was one of the most common materials for wall construction, and timber was used for floor structures.

In the basement, the walls of the main load-bearing structure are 120 cm thick on the building's outer perimeter (along the eastern facade), 114 cm and 85 cm thick (along the

western facade), 105 cm thick along most of the northern facade, and 79 cm thick along the southern facade. On the building's outer perimeter, sections of the masonry construction that form the bases of the pilasters and the half-columns are 134 cm thick. On the ground floor, the walls are slightly thinner, measuring from 87 to 105 cm on the western facade, but the bases of the pilasters and half-columns remain 134 cm thick. Inside of the ground floor plan, wall thicknesses range from 40 to 70 cm. On the first floor, the thickness of the walls mostly retains the dimensions of the load-bearing structure of the previous floor, with the perimeter walls being identical to those on the ground floor. Interestingly, in the western wing, parts of the walls in the longitudinal direction of the building (within the interior floor plan) are slightly eccentric compared to the wall axis on the ground floor (although they have the same thickness). On the second floor, the thickness of most walls is reduced. A reduction in wall thickness is noticeable on the southern facade, where it is now about 20 cm thinner (around 55 cm), while at the other walls it ranges from 10 to 20 cm. In the attic, the wooden structure of the double-hung roof is largely hidden due to the utilization of the space and the covering of the original structure with plasterboard, although elements of the wooden roof structure remain visible. What was particularly interesting about the building and required inspection was the method of constructing the floor structures throughout the building. Based on the thicknesses and rigidity of the structures, which can be felt when moving through the space, it can be concluded that the floor structures may have utilized an exceptionally strong and rigid structure of timber beams (with short spans and supported by a series of steel beams visible in the spaces on all floors). It was more probable that a type of concrete floor structure was used (concrete slabs built on smaller spans, possibly partially reinforced, as there was a practice of constructing such RC structures in Croatia during that period), which could adequately provide the necessary spans over these shorter distances. Figure 18 shows the 3D representation of the floors with load-bearing walls.

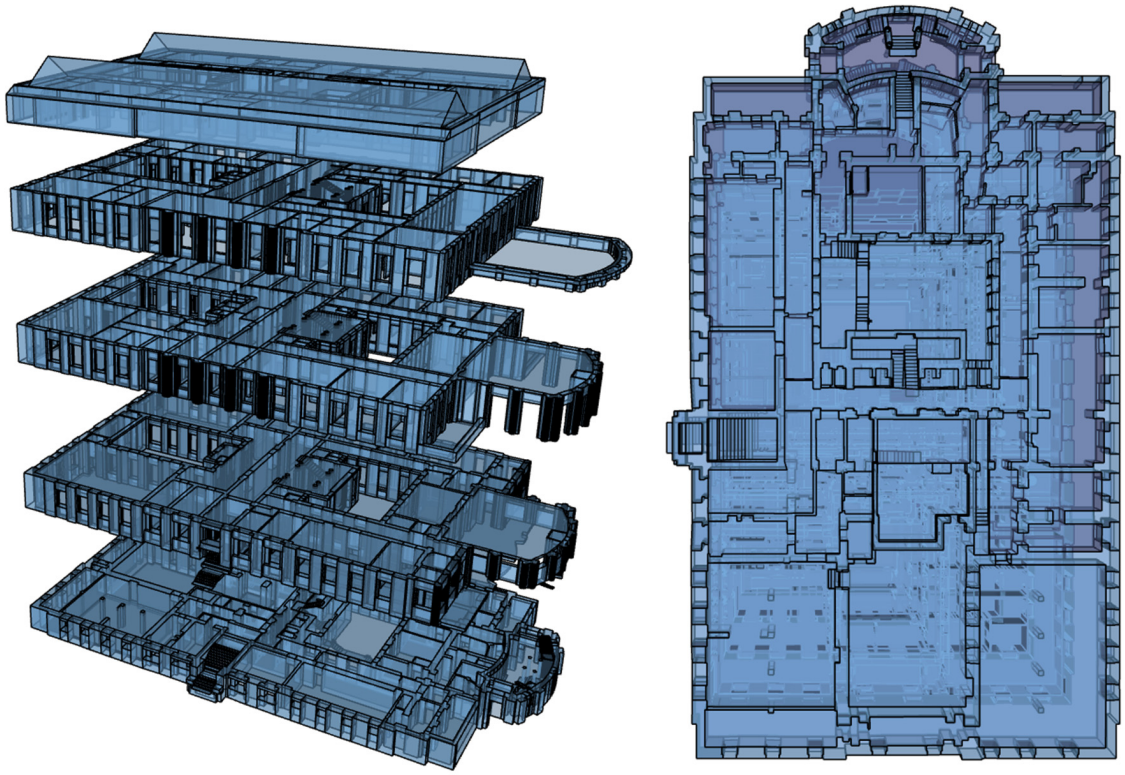


Figure 18. 3D model and one floor plan (perspective view).

3.2. Material Investigation Work

A brief summary of the material testing process is presented in this section. The following tests were performed:

- Exploratory drilling of foundations to determine the depth and dimensions of the foundation footing (three testing locations).
- Testing of the compressive strength of concrete (nine testing locations).
- Manual opening of the ceiling structure (one testing location).
- Manual opening of beams and columns to determine the layout, quantity, diameter, and condition of the reinforcement in RC parts of the building (one testing location).
- Determination of the thickness and type of attic floor (drilling through the floor structure using a diamond crown with water) (one testing location).
- Determination of the type of lintels through manual opening and drilling and identification of the position, type, quantity, and condition of embedded reinforcement (one testing location).
- In situ testing of the shear strength of mortar in joints relative to normal compressive stress conducted in accordance with the ASTM C 1531-16 [25] standard (12 testing locations), as shown in Figure 19.

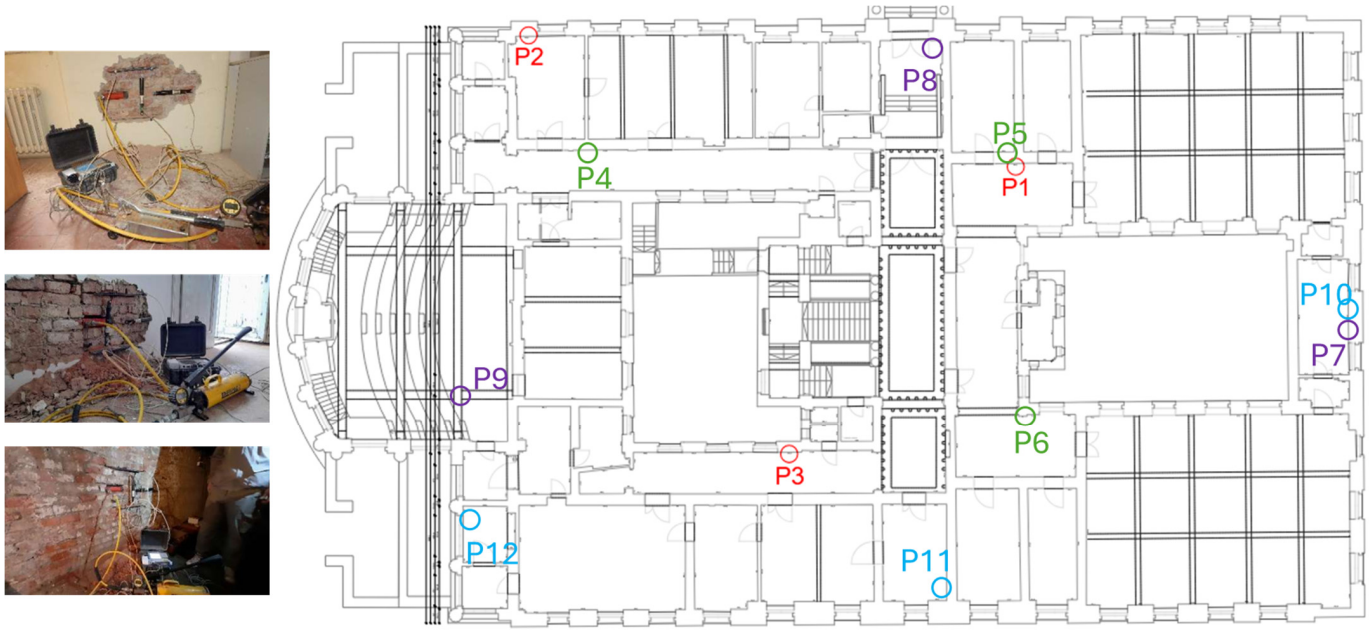


Figure 19. In situ testing of shear strength with test locations in the case study building (P—position number, red color—ground floor, green—1st floor, purple—2nd floor, cyan—3rd floor).

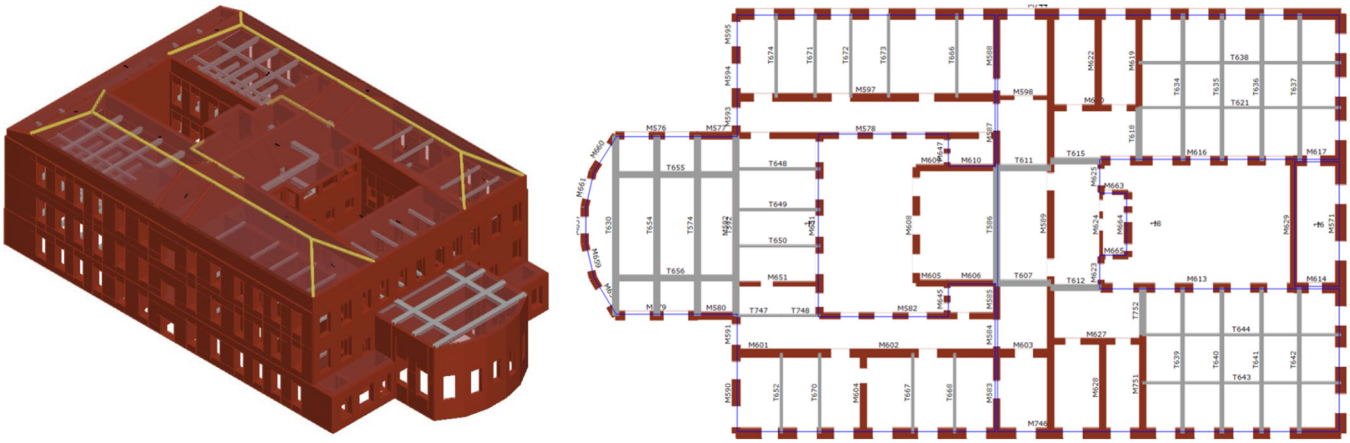
The determination of the depth and dimensions of slabs and foundations was conducted at six testing locations. Samples with diameters of Ø100 and Ø50 were drilled using a diamond crown drill through all layers to possible depths. The compressive strength was tested in accordance with the HRN EN 12390-3 [26] standard, and the density was tested in accordance with the HRN EN 12390-7 [27] standard on samples extracted from the structure, following the HRN EN 12504-1 [28] standard. Manual opening of the structure revealed that the RC column consists of smooth reinforcement bars with a diameter of Ø8, connected with stirrups of Ø6, while the beam contains ribbed reinforcement bars with a diameter of Ø18, connected with stirrups of Ø6. The concrete cover thickness is 2–2.5 cm for the beam and 8–10 cm for the column. The foundations were found to be made of concrete, with a depth of 65 cm. The mean shear strength of the masonry was 0.18 N/mm^2,

while the average shear strength of the masonry without the influence of vertical stress was 0.13 N/mm^2.

4. Numerical Modeling

4.1. Modeling of Existing Condition

For the purpose of knowing the initial seismic resistance of the existing structure, a 3D numerical nonlinear model was created using 3Muri software [29] (Figure 20). This model was employed for a nonlinear static analysis of the structure using the pushover method. The analysis was conducted in accordance with Eurocode 8 [16]. According to the Croatian Law on Reconstruction [13], the first step in assessing the condition of a structure is to prepare a basic structural report, which also includes a preliminary estimate of seismic capacity. This report, along with the condition assessment, serve as the basis for the reconstruction project, defining the level of required strengthening, financial resources for post-earthquake reconstruction, and an estimate of renovation costs. The guidelines permit the use of both linear and nonlinear models. The authors acknowledge that a detailed plan for material testing is necessary for an in-depth assessment and the implementation of nonlinear testing; in Croatia, this typically involves flat jack and shear tests supplemented with the MQI method [30]. The numerical model presented in this study provides preliminary insight into the potential behavior of the structure—the geometry, materials, and detailing are known, but the mechanical properties of the materials are assumed based on a basic testing campaign and the existing literature. In addition, the case study building is quite regular in plan and in height, so estimation through pushover analyses can give useful information [31].



Type	Colour	Description
Concrete		EN 1992-1-1:2005
Rebar steel grades		f_y=240 N/mm^2, f_u=360N/m^2
Timber		EN 338:2002
Masonry		Tests

Figure 20. Nonlinear model in 3Muri software.

The macro-element method is chosen for its balance of computational efficiency and accuracy. This approach relies on the equivalent-frame method, which utilizes nonlinear beam elements categorized into piers, spandrels, and rigid nodes. Nonlinear static pushover analysis [32] is used to evaluate the overstrength ratio employed in linear analysis, offering a comprehensive understanding of critical structural components, potential failure modes, and the overall behavior of the building. The pushover analysis involves applying constant

gravity loads along with incrementally increasing horizontal loads. Accidental eccentricity is also factored, using an adjustment of 5% of the building's length on both sides in the x (longitudinal) and y (transverse) directions. The analysis employs the Turnšek–Čačović constitutive model, which is suitable given that diagonal cracking is typically the main failure mode for URM structures [33,34]. The 3D model represents floors as horizontally rigid diaphragms, an approach considered precise enough due to the actual in-plane stiffness of the floor structures. In the software, these diaphragms are modeled with infinite axial in-plane stiffness while accounting for the actual mass of the floors. Many old URM buildings of a similar type have an unfavorable distribution of seismic forces due to the traditional use of flexible timber floors [35]. For the seismic analysis, the roof is excluded from the load-bearing system, as it does not significantly impact the building's overall response or contribute to its seismic resistance.

As said before, the material characteristics used in the numerical model are values given by basic on-site testing and derived from the literature [36–38]. Based on a thorough visual inspection, detailed laser scanning, and a geometrical survey accompanied by inspections of detailing and the connections of structural elements, a knowledge level of two (normal knowledge) was established. The building is classified as an importance class III structure due to its critical seismic performance requirements, resulting in an importance factor of $\gamma I = 1.2$. The analysis uses two Peak Ground Acceleration (PGA) values corresponding to two limit states. As per the "Law on the Reconstruction of Earthquake-Damaged Buildings in the City of Zagreb, Krapina-Zagorje County, and Zagreb County (NN 102/2020)" [13], the return period for the ultimate limit state may differ depending on the strengthening level required for older masonry buildings damaged by recent earthquakes.

Elastic response spectra for acceleration are computed, taking into account the parameters specific to soil type C, as determined at the building's site. For the site location, the PGA for a return period of 95 years is a_{gR} = 0.126 g, while for a return period of 475 years, it is a_{gR} = 0.251. The analysis encompasses 24 pushover simulations, considering both the x- and y-directions in both orientations, with two load patterns and accounting for both positive and negative 5% accidental eccentricities. Table 2 shows the results of pushover analyses and possible damage to walls for the return period of 475 years.

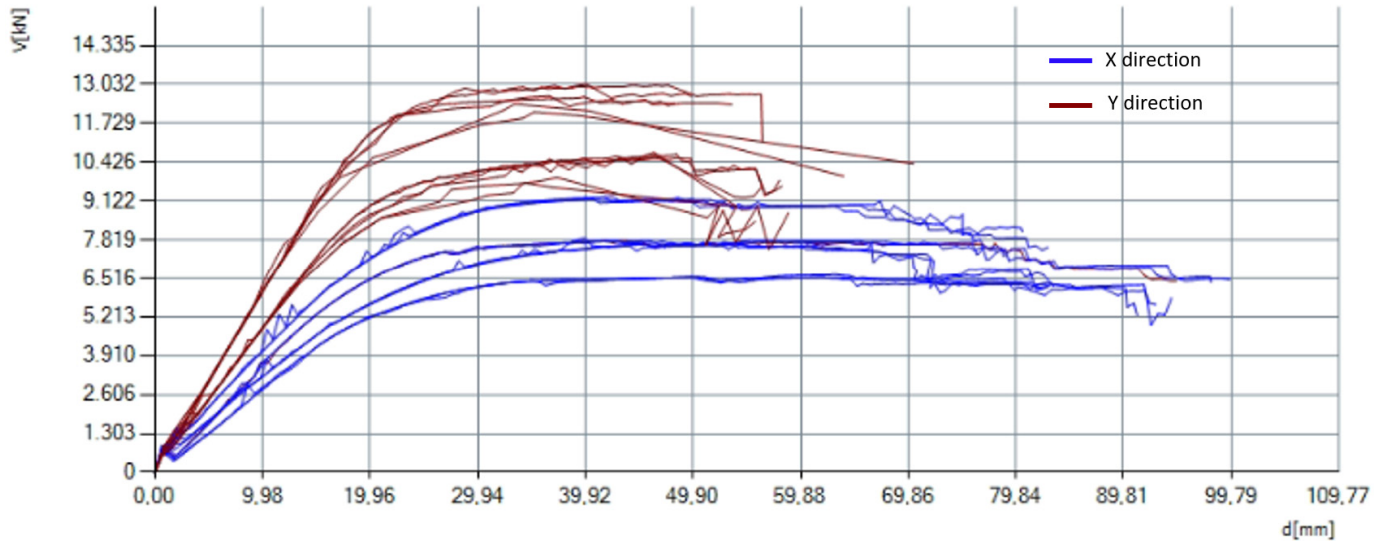
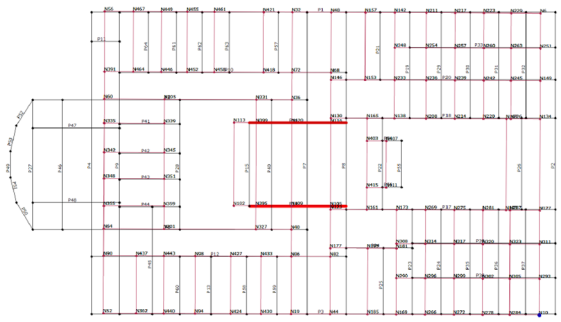
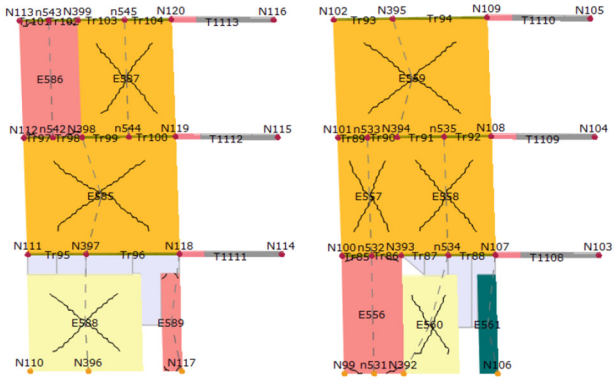


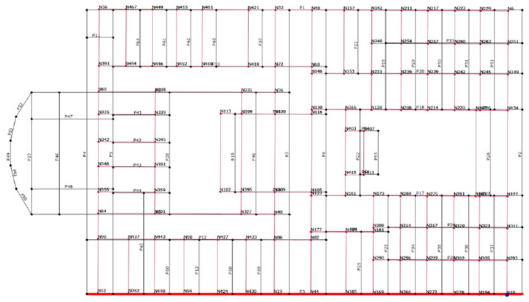
Figure 21. Relationship between the base shear force and the displacement for a structure that has not been strengthened.

Table 2. The results of the pushover analyses for the selected walls with failures in different colors.

	R.C.		**Masonry**
	Undamaged		Undamaged
	Shear failure		Plasticity incipie
	Bending damage		Shear damage
	Bending failure		Incipient shear failure
	Compression failure		Shear failure
	Tension failure		Bending damage
	Shear failure		Incipient bending failure
	Wood		Bending failure
	Undamaged		Serious crisis
	Bending failure		Compression failure
	Compression failure		Tension failure
	Tension failure		Failure during elasitc phase
			Ineffective element







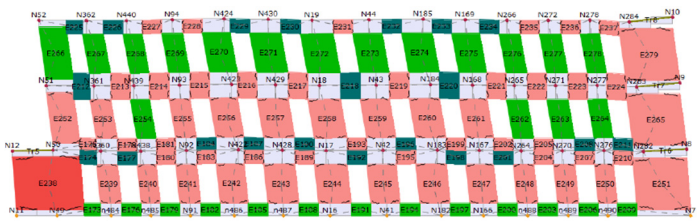
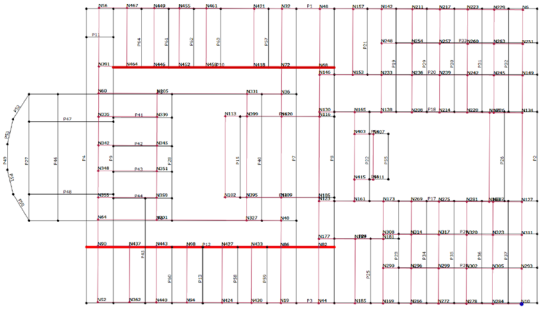
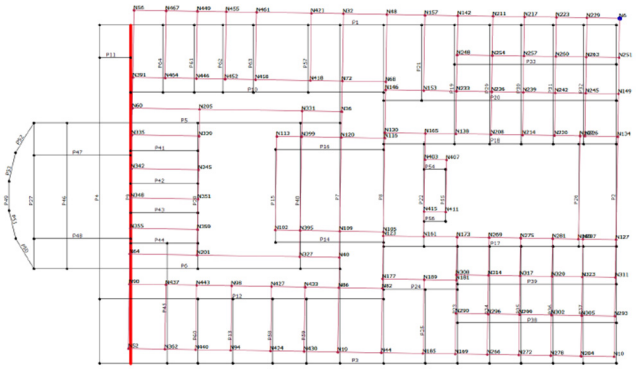
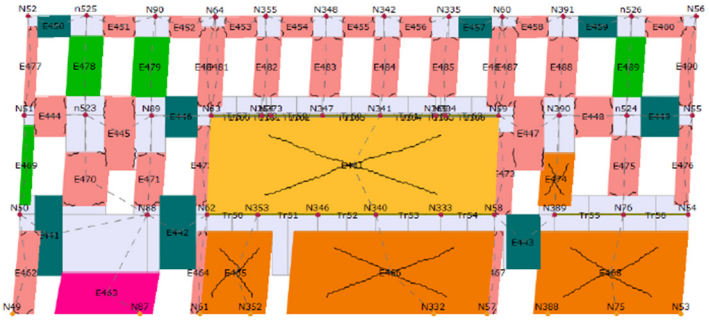


Table 2. *Cont.*

R.C.	Masonry
	
	

The seismic analysis results in a capacity curve that illustrates the relationship between the base shear force and the displacement of a designated control node. This control node is positioned near the center of mass on the building's top floor. Figure 21 displays the capacity curves obtained from all 24 analyses for a structure that has not been strengthened.

Based on the calculation results, it can be concluded that the building does not meet the criteria for any of the analyses conducted for either the Damage Limitation (DL) limit state or the Significant Damage (SD) limit state. The most unfavorable analysis for the X direction showed that the structure could withstand only 37.5% of the design PGA for a return period of 475 years. For the Y direction, the most unfavorable result showed that the structure could withstand only 32.3% of the design PGA for the same return period.

4.2. Seismic Strengthening

Considering the heritage value of the building, it was necessary to propose option(s) for seismic strengthening of the structure. To find the optimal solution, several strengthening methods were considered, and the final one, strengthening masonry walls with shotcrete, is presented here in the document.

In addition to strengthening the building against horizontal actions according to the HRN EN 1998, the structure has also been verified for vertical loads in accordance with the latest regulations and standards. This primarily refers to the local verification of floor slabs, secondary and main beams, and columns.

A minimum shotcrete thickness of 8 cm has been specified for all floors. The shotcrete used is concrete of class C25/30, with a reinforcement mesh varying between Q503, Q335, and Q257 depending on the specific position. In the graphical representation in Figure 22, the red walls represent masonry walls strengthened with shotcrete modeling.

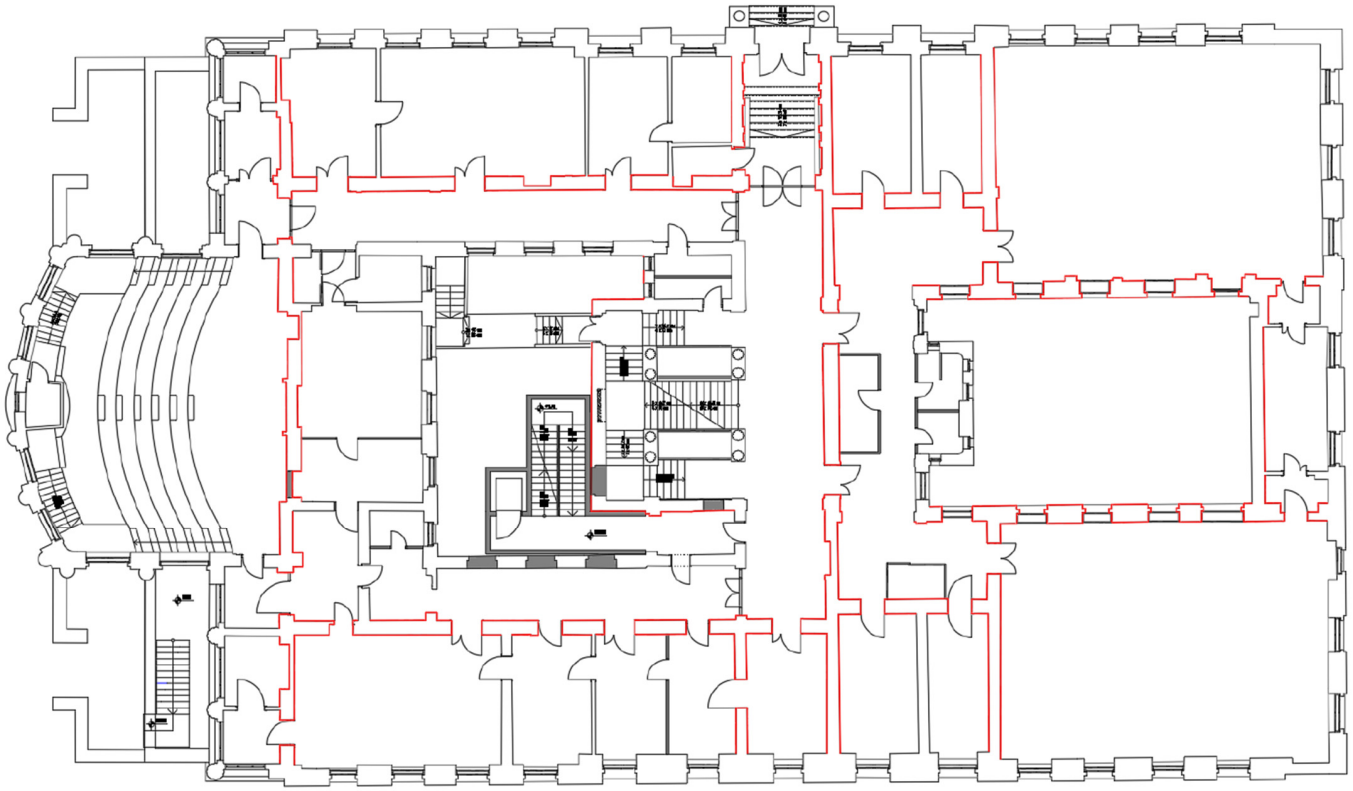


Figure 22. Structural strengthening solutions (shotcrete) on the ground floor.

Also, it is necessary to remove the existing concrete partition walls, which are approximately 7 cm thick, in the rooms on the southern part of the building's second floor. New lightweight partition walls made of gypsum boards, with a thickness of 5–7 cm, will be constructed in the same locations (Figure 23).

Similarly to the nonlinear analyses of the existing structure, nonlinear modeling of the strengthened structure is obtained. According to the results of the conducted calculations, the building meets the deformability criteria in all analyses for the significant damage limit state in the Y direction, with a minimum significant damage index of 0.75, as required by Croatian regulations

Croatian regulations also define the IZO index as the ratio of calculated earthquake resistance and construction requirements for the limit state of significant damage.

As for the unstrengthen structure, the relationship between the base shear force and the displacement of a designated control node obtained from all 24 analyses is presented in Figure 24 for the strengthened structure. In the X direction, most analyses are satisfied with the most unfavorable analysis, where the structure had a significant damage index of 0.737, which Croatian regulations require for this type of structure (public structures). This means that this structure has a resistance of 73.7% to earthquakes according to EN 1998 (defined for new structures) as shown in Figure 25. If we compare resistance before strengthening

and after, we can see a difference of almost double for the strengthened structure vs. the structure that has not been strengthened.

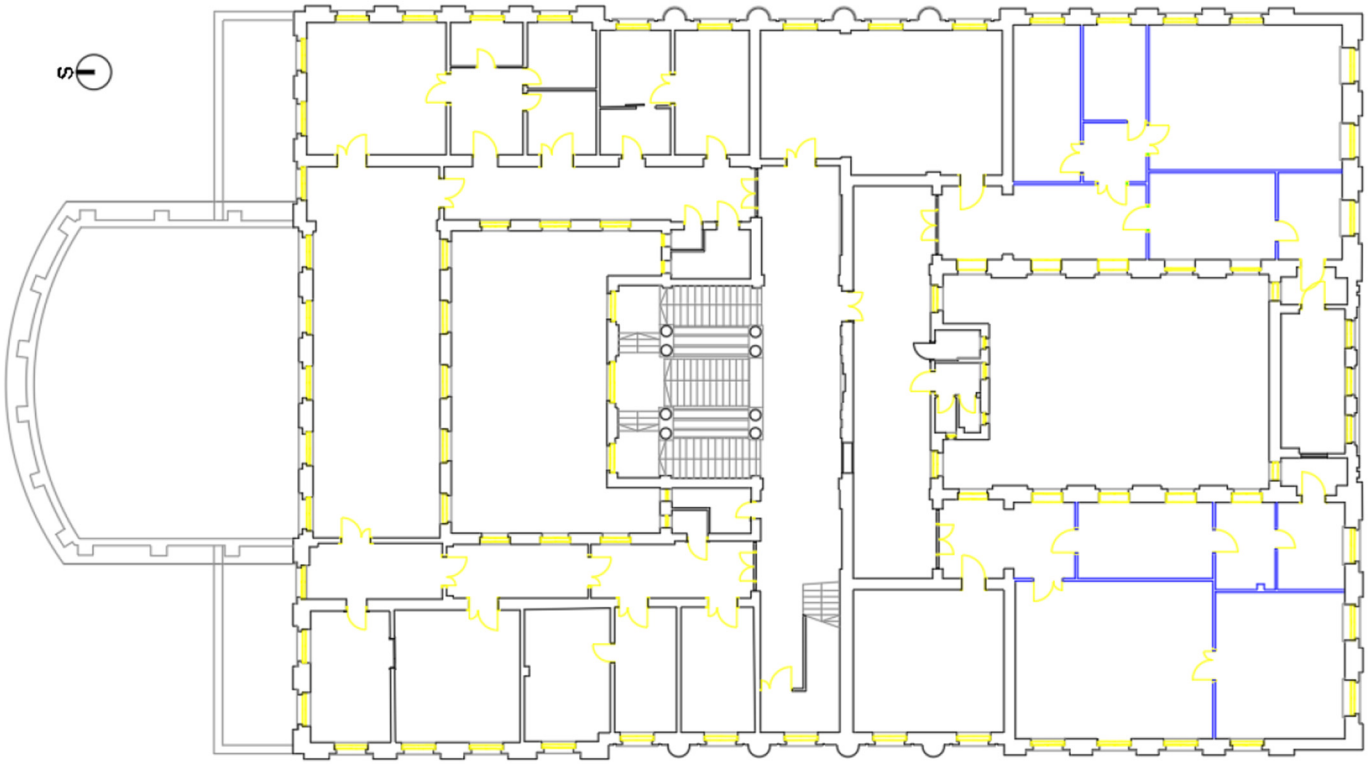


Figure 23. Locations for the removal of existing concrete partition walls—floor plan of the 2nd floor (blue color).

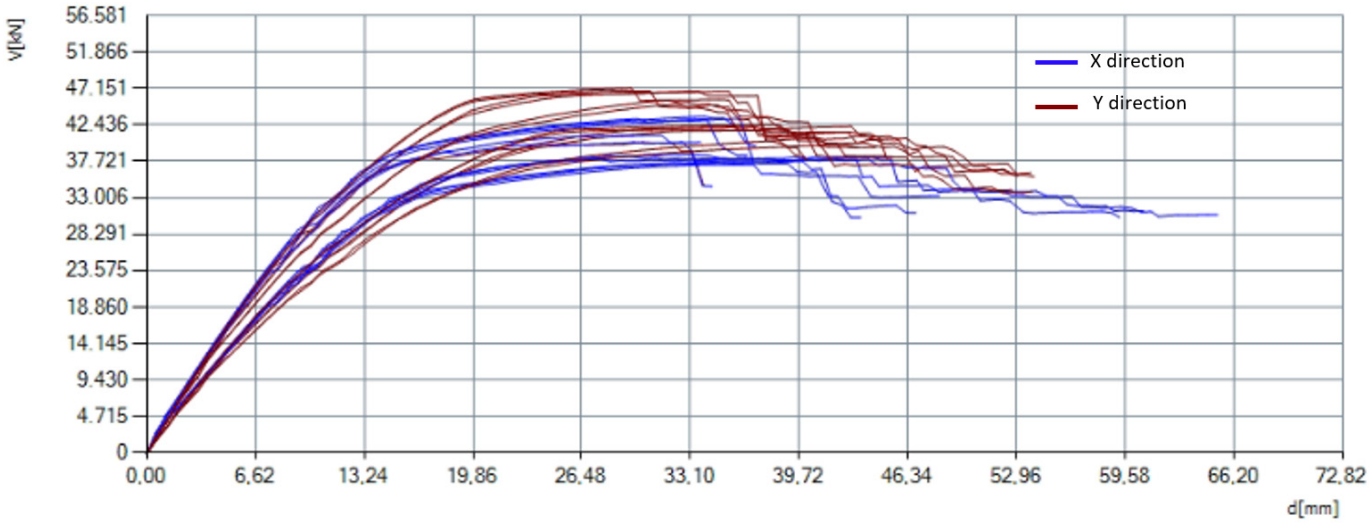


Figure 24. Relationship between the base shear force and the displacement of the strengthened structure.

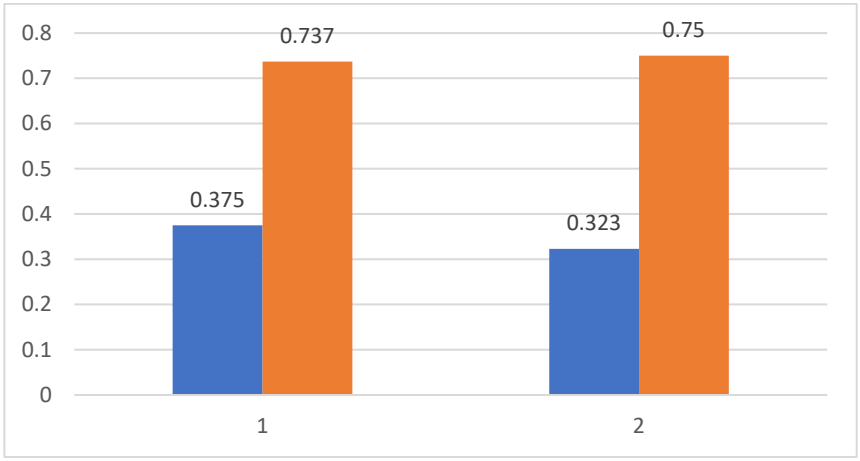


Figure 25. IZO index for the existing structure and the strengthened structure.

5. Conclusions

Earthquakes, despite their frequency, often catch communities off guard, as seen in the recent seismic events in Croatia. These disasters resulted in extensive damage to a wide array of buildings, from residential structures to educational, healthcare, and other public facilities. Many of these buildings are constructed from unreinforced masonry and frequently located in the most culturally and historically significant areas of cities. For example, in Zagreb, the protected urban zone—an area vital to the city's identity and tourism potential—suffered significant damage. These structures not only fulfill functional roles but also embody the cultural heritage and societal identity of the community, making their preservation and strengthening a priority.

This study provided an overview of the historical and architectural significance of a representative URM building within a protected zone in Zagreb. A detailed architectural analysis was performed, illustrating how older buildings often undergo modifications during their lifespan. These changes, such as the removal of walls or the repurposing of spaces, impact their structural integrity and complicate efforts to assess their seismic performance. To document the architectural and geometric characteristics of the structure, advanced tools like laser scanners were utilized, showcasing their value in heritage preservation and seismic assessment. Additionally, a conservation study was undertaken, which, although not legally required due to the building's status as part of a protected zone rather than an individually listed monument, highlights the importance of aligning conservation practices with seismic strengthening strategies.

While the case study building did not suffer catastrophic damage during the earthquake, it exhibited noticeable vulnerabilities. It remains a vital part of the architectural heritage and plays a significant societal role. Preliminary inspections and material testing were conducted in line with Croatian guidelines and norms. Although detailed material testing was not performed, existing data from similar studies, such as flat-jack testing on buildings with comparable typologies and construction periods, were incorporated. This approach reflects the practical challenges faced in Croatia, where the sheer number of structures requiring assessment and retrofitting necessitates pragmatic solutions. While this methodology is acceptable within the current professional framework, it does have limitations. Future research should prioritize more extensive material testing to improve the knowledge base for nonlinear modeling and advanced seismic analysis. Anticipated updates to Eurocode standards are expected to introduce revised testing procedures and parameters.

The study also explored conceptual strengthening techniques, including the use of shotcrete—a method permitted in Croatia, though restricted in many other countries due to its potential impact on heritage authenticity. In this case, the lack of individual heritage protection for the building allows for such interventions aimed at improving structural safety.

This paper offers a contribution to the field of earthquake engineering and heritage conservation. By serving as a practical reference, it provides architects and engineers with insights into seismic strengthening strategies for similar structures. As a case study, it applies existing regulations and standards, illustrating their potential and their limitations. The findings emphasize the need for comprehensive frameworks that integrate conservation principles with modern engineering practices.

The challenges highlighted in this study are not unique to Croatia. Similar research has been conducted in other regions with a rich architectural heritage, such as Italy and Greece, where URM structures are prevalent. These studies underscore the need for multidisciplinary approaches that combine engineering, conservation, and urban planning to address the complexities of seismic upgrading in heritage contexts. For example, studies on retrofitting historic buildings in Italy after earthquakes provide valuable parallels, as they involve similar typologies and retrofitting challenges [39–41]. As the number of such studies grows, they will collectively serve as a foundation for professionals to better prepare for future seismic events. In addition, this article can serve as a database for future research incorporating new technologies. By providing data on observed damage, it lays the groundwork for innovative approaches, such as generative design [42], which could be employed to predict potential future damage scenarios.

By integrating traditional practices and innovative tools and techniques, it offers a pathway for future research and practical applications in the field.

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