Seismic Effects on the Stone Masonry of Rubik Church in Albania: Interaction Modeling of Different Masonry Panel Types

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Abstract

The church monastery 'Shelbuen' Rubik in Albania has tourist and historical values, as it is made in a different style from most historical monasteries in the country. On 26 November 2019, the church was hit by an earthquake.

This research examines the damage resulting from this earthquake on its masonry and structural elements, as well as their interactions. The research aims to ascertain the extent of damage to the stonework in the church and its seismic resistance. It seeks to propose options for interventions to restore and strengthen the structure.

To select interventions, different types of masonry walls of the church are analyzed. different connections of the structural elements are also analyzed, using computer simulations of the whole system in different variations to identify problems and test the effectiveness of their solutions. Geographical and historical data on seismic activity in the region are studied to assess future threats.

The paper proposes to carry out a thorough restoration of the masonry walls, restoring the roof and the drainage systems, while adding structural reinforcement to the cracks that have formed to avoid their enlargement. This is to improve the resistance of the Rubik Church to earthquakes and to preserve its historical value. Such techniques will significantly improve the earthquake resistance of the church particularly with regard to shear and seismic displacement.

Keywords: Shelbuen monastery, Restoration, Earthquake, Lime mortar, Structural reinforcement.

Introduction

Cultural heritage sites, especially masonry sites (churches, mosques, bridges, fortifications) are highly vulnerable to seismic activity. Dogan et al. (2021) and Kilic (2023) show the damages that seismic activity can cause and assess the consequences of the destruction of houses and cultural monuments using Turkey as an example. In the case of Albania, the consequences were not that destructive because of the less densely built-up cities. Accordingly, the Rubik monastery was less damaged than the Turkish historical sites, due to the weaker earthquake and its relatively good location away from the urban built-up areas. However, documentation in recent years indicates that earthquakes in Albania quite often harm the structural stability of cultural monuments and buildings located in the nearby epi-center zone (The United States Geological Survey, 2023). The damage and eventual destruction of cultural monuments have a rather strong impact on the country's underdeveloped tourism industry. They deprive the country of its cultural heritage and historical monuments.

According to Bilgin et al. (2022) and Freddi et al. (2021), the 26 November 2019 earthquake in Albania near the small town of Mamurras of magnitude 6.4 was the strongest in a century and had devastating consequences. Official figures have confirmed that 51 people died and the economic damage was in the region of $1.2 billion. This seismic activity left thousands of people homeless, unemployed, or psychologically affected. According to a survey, a large proportion of respondents saw negative consequences in their homes (72%), family assets (48%), and children's education (43%) (Gega, 2020). A relatively large proportion of economic losses are caused by damage to houses and buildings of historical and cultural value, as well as the cost of repairing and restoring them.

However, because earthquakes cannot be avoided, it is necessary to consider strengthening structures in areas where seismic activities may occur (Kutsova et al., 2008). In particular, old masonry structures need to be reinforced to preserve their historical, cultural values and to improve their seismic resistance. This article examines the Rubik's Shelbuen church monastery, which is one of the oldest in northern Albania and also has a style that is practically unused in the country.

The research aims to understand the consequences of seismic activity on cultural monuments and buildings, using the case of Albania as an example. This includes evaluating the impact on structural stability, economic losses, and socio-cultural aspects. It intends to propose strategies for strengthening structures in seismic-prone areas, focusing particularly on old masonry structures. The goal is to enhance the seismic resistance of these structures while preserving their historical and cultural value. The study suggests interventions for the restoration and strengthening of the Rubik's Shelbuen church monastery. These interventions are intended to enhance the structure's ability to withstand natural disasters, especially earthquakes, based on lessons learned from the 2019 earthquake.

The objectives of the study are:

1. To conduct a detailed architectural analysis of the Rubik's Shelbuen church monastery, focusing on the different types of masonry and their interactions, particularly in the context of earthquake damage.
2. To document the effects of seismic activity on cultural heritage sites, comparing the outcomes in different regions (Turkey and Albania) to understand varying levels of impact.
3. To contribute to the preservation of cultural heritage by offering practical insights and recommendations for safeguarding masonry structures, like the Rubik's Shelbuen church monastery, against seismic activities and natural disasters.

Review of Literature

This research study holds significant relevance by combining historical preservation with engineering analysis to address real-world seismic challenges. Its contributions extend beyond the specific case of the Rubik Church, offering insights that are valuable for architectural preservation, seismic engineering, and cultural heritage protection. The paper reflects the ideas of some researchers who also consider and raise the problem of damage resulting from earthquakes on cultural memorials.

Mallardo et al. (2008) investigate the seismic behavior of an important Renaissance Palace in Ferrara (Italy), Palazzo Renata di Francia. The authors dwell on enhancing existing numerical methods and developing novel tools to analyze the mechanical behavior of historical masonry structures. Mallardo et al. have focused on simulating their response to failure, considering material heterogeneity and unique constituent properties. The main facade of the building has been analyzed by three different 2D non-linear models, an equivalent frame approach, an inelastic plane stress model, and a homogenized kinematic limit analysis. They conclude that particular care should be used by practitioners in the use of equivalent frame models, even if the results provided by this approach are in acceptable agreement with more sophisticated procedures. Indirli et al. (2013) offer an overview of the dynamic characteristics of the earthquake and the seismic history of the L'Aquila region. Indirli et al. (2013) describe and review the main characteristics of URM buildings, the building behavior and damage, with due respect to the characteristics of the earthquake, as well as concerning the structural and non-structural characteristics of buildings.

Somma et al. (2022) makes a significant contribution to the studied topic. They focus on addressing the challenge of preserving historic buildings while mitigating seismic risk, which often requires invasive interventions. They investigate the effectiveness of Geotechnical Seismic Isolation (GSI) using a centrifuge test, specifically examining the impact of laterally disconnecting a shallow foundation from the surrounding soil to reduce structural demand during seismic events while maintaining the building's integrity. As a result, in the case of pre-existing masonry structures with load-bearing walls traditionally constructed by thickening and embedding them deeply into the ground, lateral disconnection emerges as a cost-effective and considerate strategy for enhancing seismic resilience.

Sanctis et al. (2022) consider the side effects and intervention criteria for seismic risk mitigation in the ancient city of Pompeii. The study investigates seismic risk mitigation strategies in Pompeii, focusing on the restoration of the Insula dei Casti Amanti, a block of masonry buildings. The research involves site amplification analyses to assess seismic demands in excavation fronts and emphasizes the design considerations for the foundation system of a new covering structure while addressing potential resonant mechanisms between the subsoil and archaeological ruins for the protection of the ancient city from future earthquakes.

Stanko et al. (2016) and Markušić et al. (2021) look at the case of seismic impact on historical buildings. They focus on the Trakošćan Castle, a historical site in Croatia, and its vulnerability to seismic events. They utilize microtremor measurements and the Horizontal-to-Vertical-Spectral-Ratio (HVSR) method to assess local seismic responses, identifying factors like soil characteristics and ground motion influences. Additionally, they emphasize the importance of evaluating structural weaknesses, promoting restoration efforts, and safeguarding the castle's cultural heritage from the damaging effects of earthquakes.

Cosgun et al. (2023) focus on the seismic performance assessment of a historic wooden hypostyle mosque complex constructed in 1273. The mosque complex, representing a combination of wooden pillar and masonry wall construction techniques, is situated in the Anatolia region of Turkey. Through linear and nonlinear analysis methods, the research evaluates the complex's ability to withstand seismic effects following restoration, demonstrating its compliance with shear strength requirements and inter-story drift limits for different earthquake recurrence periods and ground motion levels. In conclusion, Cosgun et al. (2023) suggest that the numerical analyses presented in this paper should be considered an effective and necessary step in the restoration of such historic buildings. Underestimating the numerical analysis stage might cause serious problems in terms of the sustainability of such structures.

Kocaman (2023) investigates the seismic performance of the historical Molla Siyah Mosques, designated cultural assets by the Ministry of Tourism and Culture in Turkey. They employ advanced numerical simulation methods, involving 3D finite element models, to assess the impact of earthquake ground motions on the mosque's structural behavior, considering the influence of a concrete vault cover installed in the past. The study's importance lies in its examination of damage propagation, collapse mechanisms, and reinforcement effects, offering insights into the seismic resilience of historical masonry mosques that have not previously undergone advanced numerical analyses.

Cauzzi et al. (2015) and Kapogianni et al. (2021) focus on assessing the seismic response of the Athenian Acropolis Hill in Greece, considering its unique local site conditions and the presence of historical monuments. They employ a combination of seismic data analysis and numerical simulations to understand how the hill's geological characteristics influence ground motion during earthquakes. In the context of seismic restoration for historical masonry churches, a strategic approach involving the implementation of a dissipative roof diaphragm emerges as a valuable technique.

Longarini et al. (2018) emphasize that this approach aims to mitigate out-of-plane lateral wall movements, curb rocking mechanisms, and importantly, minimize the transmission of in-plane shear forces from the roof to the transverse frames or headwalls of the church. Many regions, guided by conservative restoration principles, prefer wood-based solutions, and this study proposes the utilization of cross-laminated panels as a dissipative roof structure. The intention is to meet seismic criteria while enhancing the response of the transverse nave. To optimize the dissipative capabilities of the cross-laminated roof structure, the investigation delves into the behavior of steel connections, both panel-to-panel and wall-to-panel, encompassing diverse configurations (Alekseev et al., 2019). They delve into varied numerical representations of these connections, applied to a specific case study. Moreover, nonlinear analyses are executed to effectively ascertain the steel connections' dissipative effects on the cross-laminated panel, with a focus on in-plane shear behavior (Tang et al., 2014).

To determine the appropriate type of intervention to rebuild and strengthen the monastery, following the seismic activity that damaged the structure, it is necessary to start with an analysis of the damage to the main facade. In contrast to Cardani et al. (2008), who studied the damage directly to the masonry of the churches after the 2004 earthquake in the northern part of Italy, this research is based on modern Italian recommendations as well as European building codes, using relatively modern technology to analyze and simulate the structure, considering the interaction of the different types of masonry in it. Once the damage has been correctly identified, the definition of interventions can be implemented based on the analysis of the damage caused and the knowledge of the structural behavior (Berikbaeva et al., 2020). The behavior of the structure can be determined by considering the empirical analysis and then verified by a detailed numerical analysis. Such an analysis considers homogeneous material within each panel of the structure and considers the overall performance of the structure with macro-element modeling, but unfortunately, numerical analysis cannot consider the connections of different types of masonry as well as heterogeneous connections (Leader, 2022; Zaurbekov et al., 2021).

Research Methodology

Rubik's Church has several types of masonry in the structure and for quality restoration and reinforcement. This cannot be ignored. Zia et al. (2013) provide a more detailed model of the site, with which the type of masonry in each structural element of the monastery can be reliably determined to further select restoration strategies. However, this is a rather expensive and time-consuming method. Thus, this article will use data provided by the Monument Institute of Albania (Albanian Government Council of Ministers, 2021).

In this research, data collection was conducted through a systematic process aligned with a case study methodology, focusing on Rubik's Monastery. The study employed a range of methodologies, including analysis, synthesis, modeling, description, evaluation, and concretization. The data-gathering approach proceeded through the following steps.

Firstly, archival data sources were meticulously utilized, incorporating information from reputable bodies like the Academy of Sciences of Albania and the US Geological Survey. These sources provided essential data, such as the current seismic micro zonation map of the site's area and earthquake intensity measures (PGA) from the seismic events in September and November 2019. These inputs were pivotal for understanding the geographical context and seismic activities in the region (The United States Geological Survey, 2023). In addition, architectural plans sourced from the Institute of Monuments of Albania were employed to construct comprehensive structural sections of the Rubik's Church (Albanian Government Council of Ministers, 2021). These plans offered vital insights into the physical layout and dimensional aspects of the building.

Numerical software played a significant role, enabling the research to execute sophisticated modeling and analysis. The "SeismoStruct" software facilitated the meticulous numerical modeling of building panels, whereas the "3Muri" software was deployed to analyze the mechanical characteristics of the materials involved. The data collection process incorporated both non-destructive and destructive methods. Visual inspections were initially conducted, providing insights into architectural damage. Concurrently, destructive methods, such as strength analysis, were undertaken on wall panels to ascertain their strength and stiffness. The study engaged in meticulous modeling and simulation endeavors. Leveraging the "SeismoStruct" software, 3D modeling was undertaken, achieving an intricate representation of the church's structural behavior. Different reconstruction scenarios were modeled and juxtaposed with the original church model to discern disparities in seismic resistance.

Finally, the collected data, which encompassed seismic micro zonation maps, earthquake intensity measures, architectural plans, and numerical modeling outcomes, underwent meticulous scrutiny and analysis. The findings were evaluated by comparing the original structure and the reconstructed scenarios, facilitating the identification of the most effective and suitable restoration strategy.

Throughout the data collection process, the research adhered to the principles of a case study methodology, thereby emphasizing a deep and focused exploration of Rubik's Shelbuen church monastery. The harmonious amalgamation of diverse data collection methodologies, modeling techniques, and software tools has enabled a thorough assessment of the structure, culminating in a well-informed and effective restoration strategy.

Findings

Rubik's Shelbuen church monastery

The church monastery of Shelbuen Rubik is situated about 70 km north of Tirana above a very steep rocky hill. The monastery church has been referred to as a Benedictine abbey since 1166, and old mosaics trace Latin inscriptions dating back to 1272. A single-nave church, oriented along the axes, East (apse) and West (main entrance). It is attributed to the Norman style, making it one of the few surviving cultural monuments of this style in Albania (Fig. 1).

Fig. 1: The facade of the church's main entrance
Source: Albanian Government Council of Ministers (2021)

The church is a stone building with stone walls. The masonry preserved from different times and typologies differs throughout the structure. The oldest preserved part is the apse walls, built almost horizontally from irregularly shaped stones joined by a lime mortar. The wall on the West side was torn down to create a connection to the new nave of the church, which was realized through a stone arch supported by stone columns. This rebuilding was done in the middle of the nineteenth century (Fig. 2).

Fig. 2: Image of the church (XIX century)
Source: Hoxha (2016)

The main facade is constructed of regular-shaped stones with pilasters. The pilasters are connected to the walls between them by a thin ball of lime mortar in most places and some places by stone blocks. The windows and doors in the monastery have a cornice in the form of a stone frame with classical stones joined by a small layer of lime mortar. Traces of ancient frescoes can be found in the part of the apse on the inside, heavily damaged by time, of the stone vaults. On the Southeast side of the apse are a buttress and wall foundations, presumably installed to avoid the movement of stone blocks towards the edge of the cliff, as the monastery is located quite close to the cliff. During the existence of the Rubik Church, the outer walls of the structure have never been plastered, but in the 90s of the 20th century, as part of the restoration work, all the outer walls except the main facade of the building were plastered. This intervention reconstructed the roof, the interior ceiling, the wooden inter-floor ceilings above the entrance, and other architectural details of the structure (Albanian Government Council of Ministers, 2021).

Damage to the Church

The earthquake that occurred on 26 November 2019 in Albania near the small town of Mamurras is the first documented seismic event to cause damage to a monastery. Structural damage is usually of two types: degradation/damage to materials and some minor structural damage (Eremenko et al., 2020). The condition of the church as it stands has now been documented by non-destructive testing and visual observation. From these investigations of the church structure, the problems can be summarized: Structural damage includes cracks in the face (Figs 3 & 4) and the vault of the apse (Fig. 5), damage and cracked masonry in the oldest part of the church – the closing wall of the east side above the apse.

Fig. 3: Cracked masonry wall above the apse
Source: Author

Fig. 4: Micro cracks in the wall of the apse
Source: Author

Fig. 5: Cracks in the vault of the apse and the wall
Source: photos were taken by the author

There are also many other problems, such as minor deterioration of the walls and plaster mortar, burning and peeling of the stone surface in the door and window frames, heavy dampness predominantly on the east side, and damage to the gutters. The bulk of the damage to the building is due to deterioration over time, but events such as earthquakes or other natural disasters contribute to an even greater deterioration. Emergency interventions to repair cracks and walls on the eastern side, based on visual observations, do not meet structural and architectural requirements.

Seismic Activity in the Monastery Area

The church is close to the most earthquake-prone areas of northern Albania. The monastery was subjected to one of the strongest earthquakes in Albania in the last century. The largest documented earthquakes in the area in the last 100 years are:

1. Earthquakes in Montenegro in 1962 and 1979.
2. Earthquake in Tirana on 9 January 1988.
3. Earthquake on 21 September and 26 November 2019.

On the current seismic microzonation map, in the area where the church is located, in A-type soil, for TR=475 years, there is PGA=0.208g (Fig. 6).

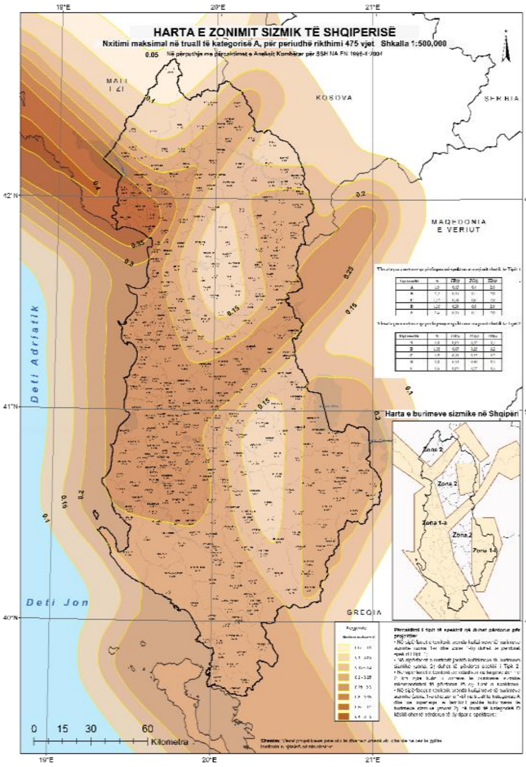

Fig. 6: Peak Ground Acceleration (PGA) map of Albania
Source: composed by the author

Seismic activity near Durresi occurring was the closest and most critical to the area where the church is located. The strongest tremor occurred on 26 November at 2:54:12 (UTC) with an estimated magnitude of 6.4 on the Richter scale near the small town of Mamurras. The activity is estimated to have occurred at a depth of about 20 km, but the magnitude of the shock was devastating (The United States Geological Survey, 2023). Several aftershocks then occurred in the area, some of them reaching a magnitude of 5.1. The earthquake killed over fifty people, injured some 2000, and rendered 4000 homeless. The damage was estimated at more than €1 billion. Fig. 7 shows the PGA values as reported by the National and Kapodistrian University of Athens.

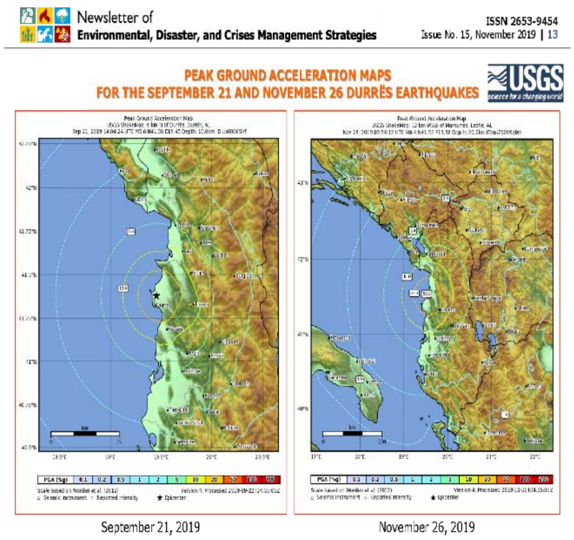

Fig. 7: PGA values in the earthquake area
Source: Lekkas et al. 2019.

Seismic wave amplification can be influenced by basin and soil properties. However, in the case of Albania, these effects are not that great due to the ground conditions of the basin (Fig. 8).

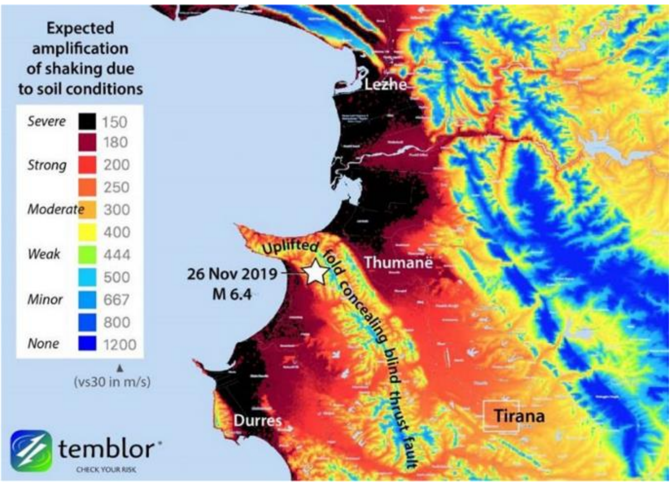

Fig. 8: Shaking amplification due to ground conditions
Source: Temblor (2019)

Although seismic data is well known at the site of the activity, a seismic survey is also carried out to detail the design parameters (Mancini et al., 2021). Tectonic maps, topographic effects, geological conditions, directionality, and possible impact near the epicenter are considered. The soil on which the monastery is located is classified as type B according to Eurocode 8 with VS30, with a value of VS30=741.1 m/s (European Commission, 2007; European Committee for Standardization, 2005).

The Structure of the Monastery

This study uses an architectural plan created by the Albanian Institute of Monuments (Albanian Government Council of Ministers, 2021). Based on this and some measurements, floor plans and structural cross-sections of the structure were made. With the help of surveillance cameras and thermal imaging cameras, it was possible to identify all the elements of the structure. Particularly the continuation of the masonry panels of the building in the form of stone strip foundations, as well as elements of masonry of various types and dates of construction. The main structural elements of the church can be distinguished:

1. The facade of the main building is lined with regular square stone masonry, as well as columns (stone pilasters).
2. The walls on the sides of the building have irregular masonry with columns in the corners.
3. The end sections feature irregular masonry elements with columns in the corners.
4. Stone vaults and arches.
5. Stone buttress.

Fig. 9 shows the church with the different types of masonry highlighted.

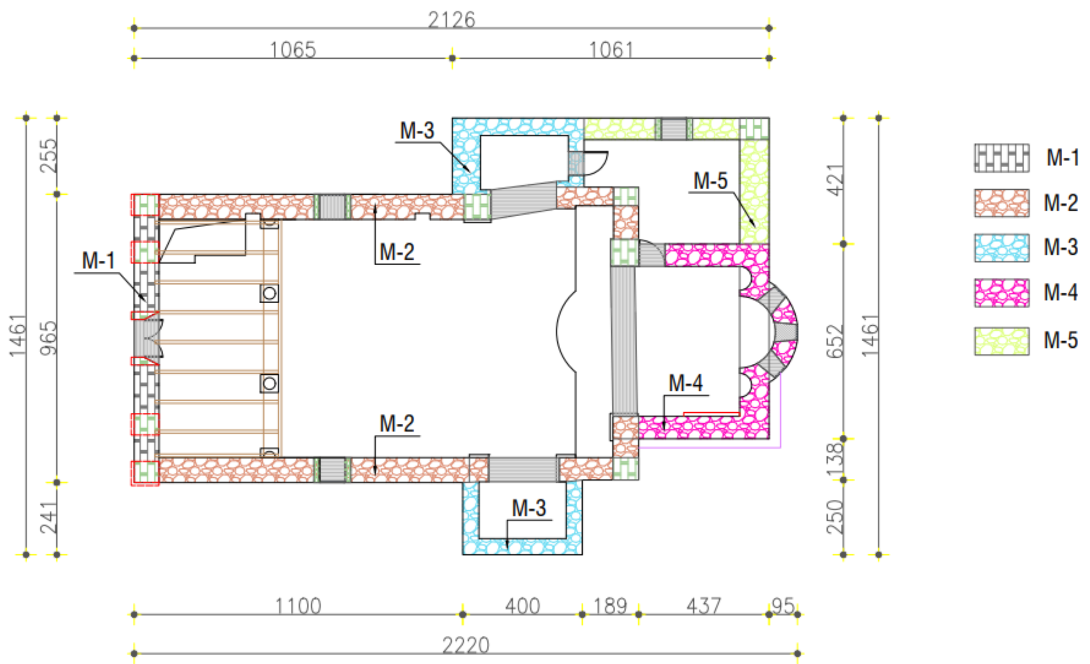

Fig. 9: Church plan with masonry types highlighted
Source: Albanian Government Council of Ministers (2021)

No changes in height depending on the structural elements were noted. Once the measurements are taken, from a geometric point of view, it can be assumed that there is complete accurate information about the structure of the building. By examining the documented data and taking into account the studies carried out by the Monument Institute of Albania (destructive tests exclusively for mortars), 5 types of wall panels have been defined (Albanian Government Council of Ministers, 2021). For each of them, an index of masonry quality (IQM) is determined, strength parameters are estimated by empirical and correlation tests, and acoustic stiffness is evaluated by acoustic tests. The table below shows the parameters of each type of masonry panel (Table 1) and the information for the IQM of the facade wall (M1) (Fig. 10).

Table 1: Stiffness and strength values for masonry walls
Source: Albanian Government Council of Ministers (2021).

Masonry parameter	M1	M2	M3	M4	M5
Stone strength (daN/cm^2); f_b	180	200	200	200	170
Mortar strength (daN/cm^2); f_m	12-17	10-16	10-15	10-16	10-13
Average strength of masonry panel (daN/cm^2); f_m (γ_i=1.5)	18	11	10.5	11	10
Strength of masonry based on EC6 (daN/cm^2); f_k	42	38	36	38	34
Shear strength (daN/cm^2); τ_o	0.45	0.15	0.15	0.15	0.15
Masonry Elastic modulus (daN/cm^2); E_m	18000	13000	13000	13000	11000
Masonry Shear Modulus (daN/cm^2); G_m	6500	4800	4700	4800	4000
Self-weight (daN/m^3); ρ	2100	2000	2000	2000	1950

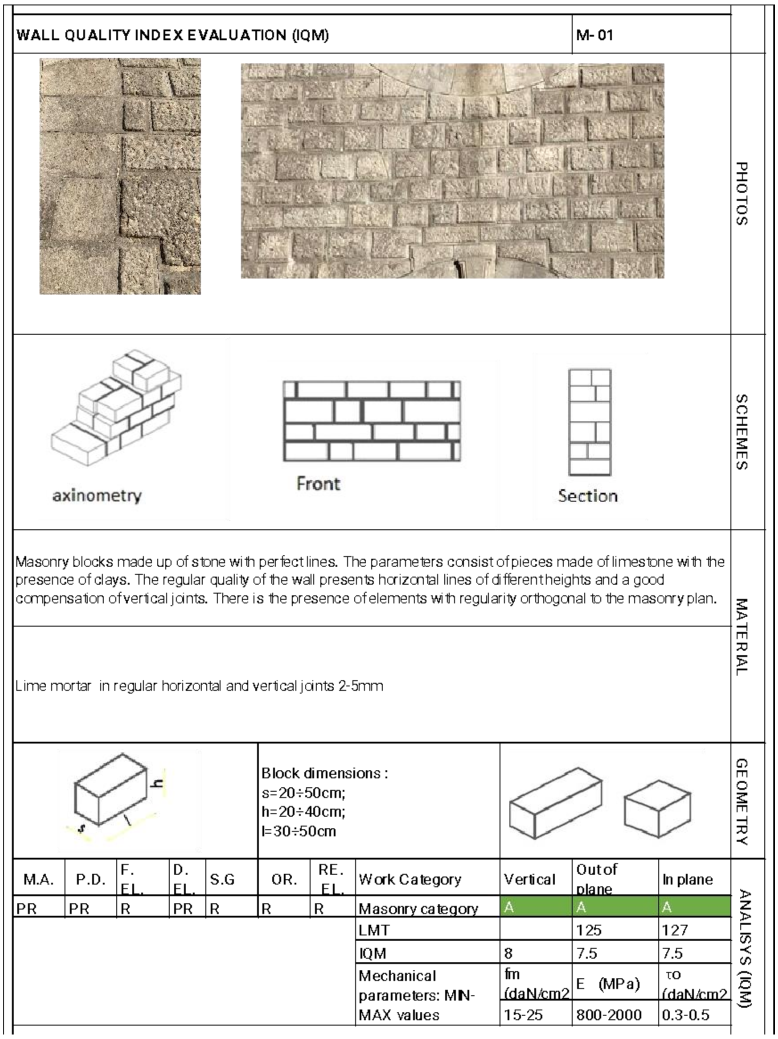

Fig. 10: Determination of masonry quality and masonry strength values of wall M1
Source: Albanian Government Council of Ministers (2021).

The strength of the masonry panels can be adjusted to the construction techniques, the width of the wall, and the thickness of the vertical and horizontal joints.

Modeling the Local Interaction of Different Types of Masonry Panels

In addition to the different types of masonry work in masonry walls, construction techniques also include different types of interaction between structural elements, such as:

1. Stone frame – Stone wall.
2. Columns (stone pilasters) – Stone wall.
3. Stone vaults, arches – Stone wall.

A non-linear analysis of the structural interactions of the stone columns (pilasters) with the stone wall was carried out using the program “SeismoStruct”. For the other two, the “3Muri” software was used to further simulate the actual design mechanism. All input parameters are chosen according to recommendations and seismic loading is according to calculation procedures (American Society of Civil Engineers, 2014; Federal Emergency Management Agency, 2006; International Council on Monuments and Sites, 2003). Models to study the local interaction of columns with masonry walls are shown in Fig. 11.

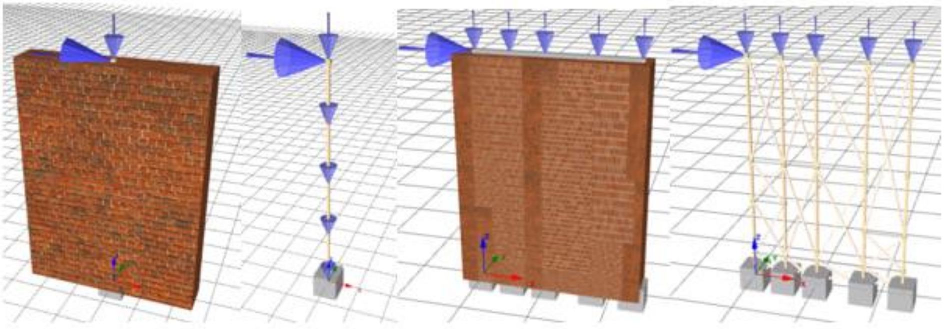

Fig. 11: Models of a homogeneous wall and a stone wall-column wall
Source: composed by the author

The stone pilasters are connected to the walls by stone blocks at 2-2.5 m. The stone columns are connected to the walls at a height of 5.5 m from the bottom of the facade panel in separate parts of 3-4 stone blocks. The model in the first figure illustrates the performance of the panel if it were a homogeneous macro element, whereas the model in the second figure is divided into columns and walls directly, simulating their discrete connections. The connections shown in the models horizontally simulate the local connections of the masonry blocks of two different types of masonry while considering that the same elastic deformations occur in each plane, without cracks (damage in the wall before the connections). Diagonal joints are the simulation of the transmission of deformation to the vertical surface of the wall or another panel from the bending of the uprights. The stiffness of these joints is equal to the stiffness of the compression strut between the columns and each panel. Here, the law of masonry behavior is described as “an inelastic masonry framework (sub-elements of a modified Ibarra-Medina-Cravinkler wear curve with bilinear hysteresis rules and pinching)”, with a parabola-type masonry model. The curves for both models and their performance are presented in Fig. 12.

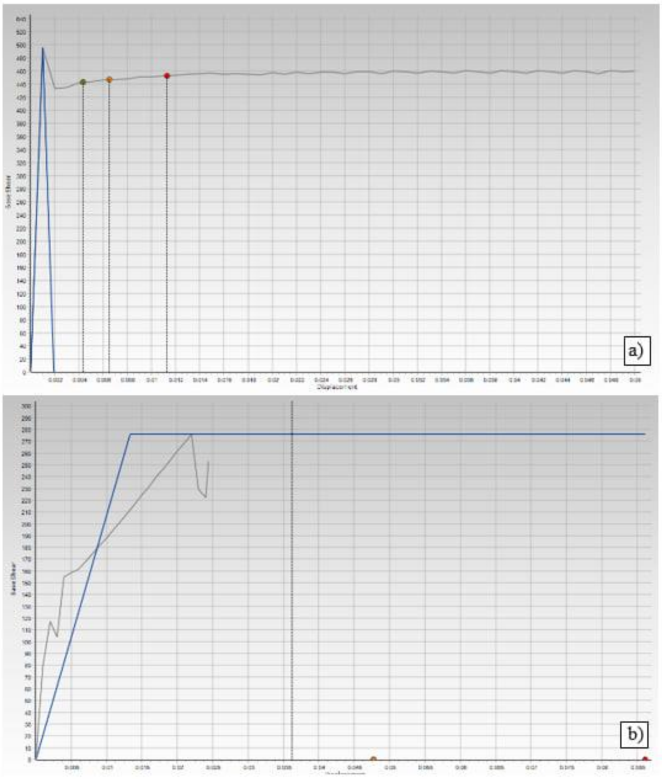

Fig. 12: Performance curve for a homogeneous stone wall and a stone wall with columns: a) homogeneous wall; b) wall with columns
Source: Author

By adjusting the stiffness and strength values of the facade wall panels it is possible to divide them with stone columns into 3 separate panels. Windows, doors, and other stone frames of the openings are modeled with the 3Muri software by fencing them using only the compression strength in these parts.

Analysis of the masonry of the stone church for a further renovation project

Using the "3Muri" software, the structure of the Rubik's church is modeled for its non-linear seismic stability analysis considering the different macro elements and plasticity concentrations. For a clearer and more correct analysis, each stone wall is modeled as a separate macro element with homogeneous material behavior, three floors according to the wooden floor in the entrance part, the vault and roof level, and its recesses, and linked to the rest of the elements. As an exception, the stone column in the facade (in the case of the second model) can be highlighted. All input parameters are adjusted according to the above recommendations (American Society of Civil Engineers, 2014; Federal Emergency Management Agency, 2006; International Council on Monuments and Sites, 2003). Fig. 13 shows the rendering representation of the computational model.

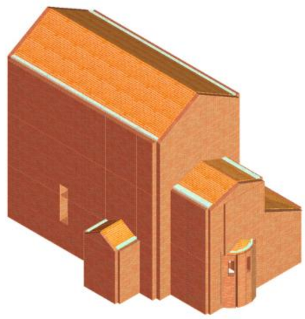

Fig. 13: A single three-dimensional view of the structural model of the church
Source: Author

The following figure shows the throughput curves of the 24 analyses for the orthogonal x and y direction and the two values of the mass distribution shape and eccentricity, as well as the main results. The analyses were performed for both models, with and without local interaction (Fig. 14a) in the stone panels (Fig. 14b).

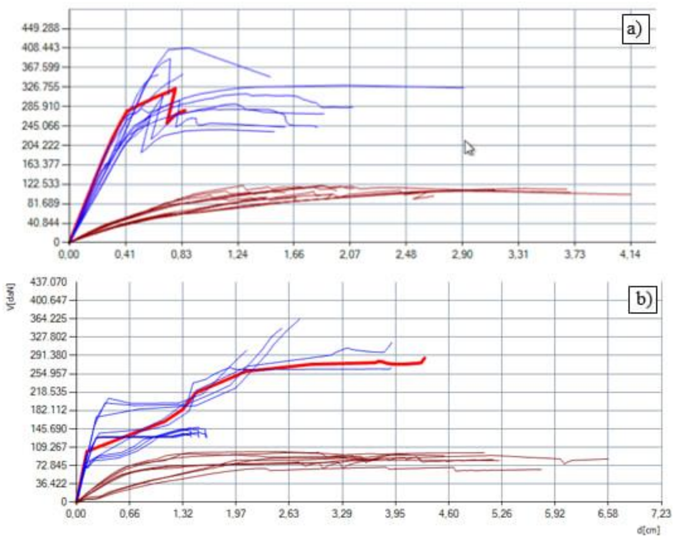

Fig. 14: Church structure capacity curves for 24 analyses: a) model without local interaction; b) model with local interaction
Source: Author

The structure was found to perform completely differently in the transverse and longitudinal directions, but in both cases, it is unable to withstand the design seismic load, resulting in damage and failure of the elements in flexure or shear. A 3D representation of the cloister with the state of the elements in it for the transverse direction in the case of the most unfavorable analysis is shown below (Fig. 15).

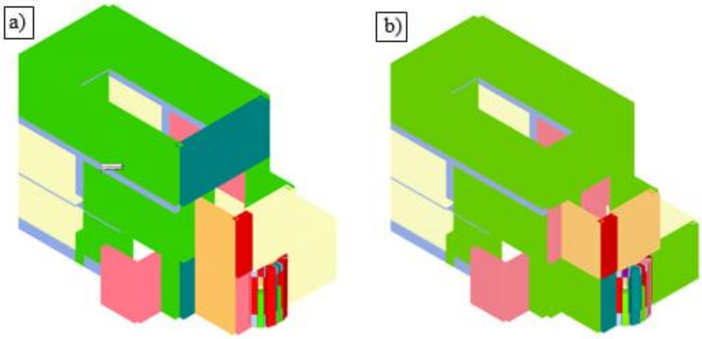

Fig. 15: Three-dimensional representation of the state of the element of the calculation model: a) without local interaction; b) with local interaction
Source: composed by the author

As can be seen, the damage in the model corresponds with the observed damage to the church after the earthquake, but the seismic load in the analysis was slightly higher.

1. Shift states:
    - green – intact;
    - yellow – damaged;
    - brown – critical damage.
2. The bend conditions of the element:
    - gray – intact;
    - bright red – damaged;
    - red – critical damage.

The following three figures show the calculation models with the most unfavorable analysis for the side wall of the structure M2 (Fig. 16), the wall at the entrance to the apse (Fig. 17), and the facade wall M1 (Fig. 18). The load-bearing capacity curve is presented together with an assessment of the condition of each structure in general and the damage to the panel elements in particular.

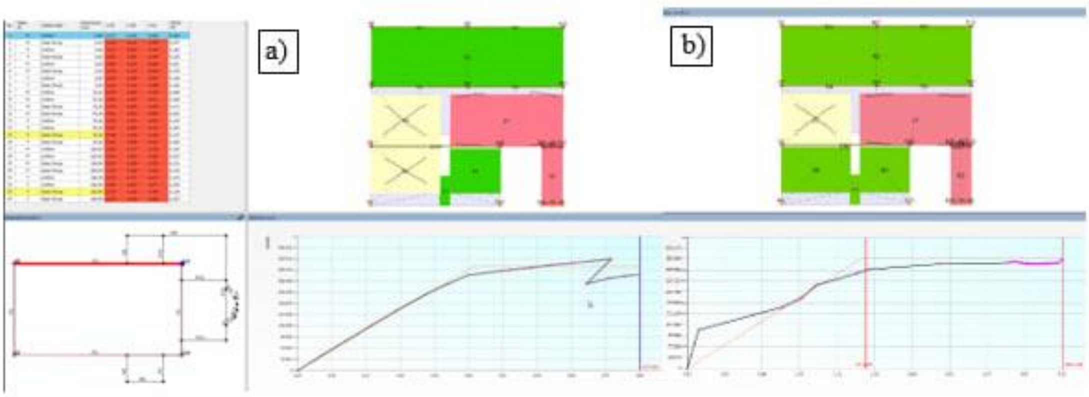

Fig. 16: Two-dimensional view of the load-bearing capacity analysis curve. The position of the panel and the nature of its behavior. (North side panel, M2): a) without local interaction; b) with local interaction
Source: Author

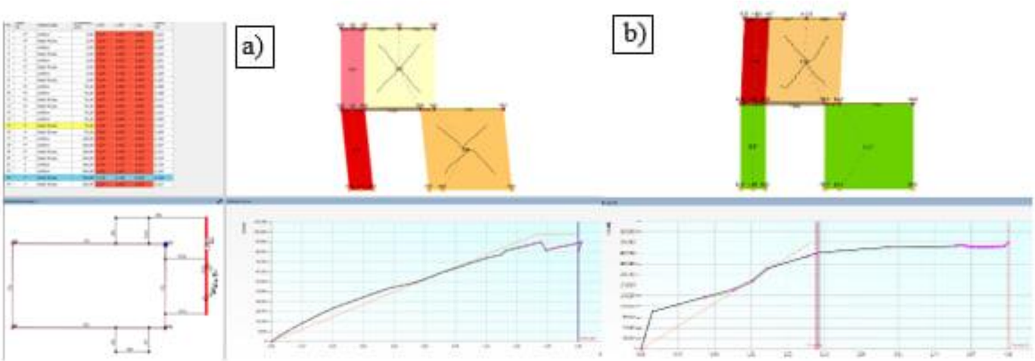

Fig. 17: Two-dimensional view of the load-bearing capacity analysis curve. The position of the panel and the nature of its behavior. (Wall at the entrance to the apse, M2): a) without local interaction; b) with local interaction
Source: Author

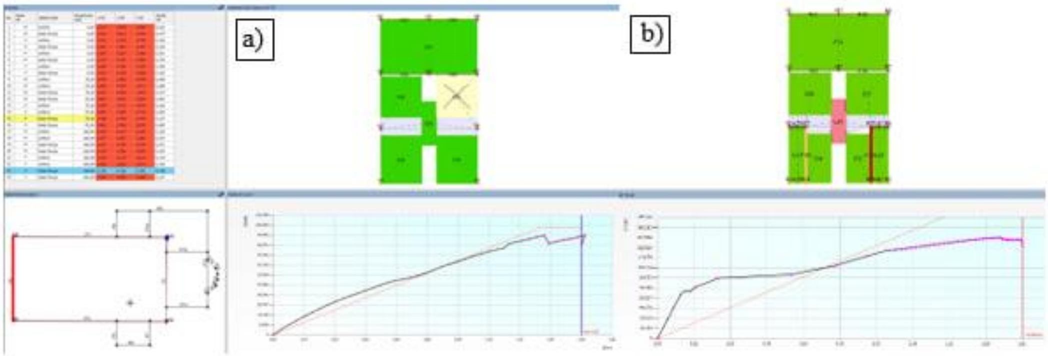

Fig. 18: Two-dimensional view of the load-bearing capacity analysis curve. The position of the panel and the nature of its behavior. (Wall at the main facade, M1): a) without local interaction; b) with local interaction
Source: Author

Velocity "α" is:

$$a_{PGA} = \frac{PGA}{a_{gR}}, \quad (1)$$

where: PGA – the power limit acceleration for all limit states regardless of the seismic load spectrum; a_{gR} – load corresponding to the seismic acceleration.

From all the analyses, tests, and investigations mentioned above, it is clear that at this time, the Rubik Church "Shelbuen" is relatively prone to seismic activity and after the earthquake, it requires conservation, restoration, and structural reinforcement (Thompson et al., 2022; Varro et al., 2021). In particular, interventions such as these can be used for this purpose (Scamardo et al., 2022; Babak et al., 2019; Onutu et al., 2022; Akhymbayeva et al., 2021).

1. Conservation of the monastery masonry:
   - getting rid of vegetation in the walls of the churchyard;
   - cleaning the frames and stones in the church walls;
   - cleaning masonry joints;
   - painting (re-plastering) plastered walls, coating them with protective resins and/or self-cleaning paint. Caulking of micro-cracks.
2. Stonework restoration:
   - removing plaster from the outside of brick walls;
   - cleaning of cracks/joints with low-pressure injections;
   - filling the joints of masonry walls with lime solution;
   - coating joints and masonry stones with anti-freeze and anti-calcification mortars;
   - periodic cleaning of the stones and renewal of the coatings.

3. Moisture and leakage protection (repair of guttering and roofing):
   - roof repair and renewal (shingles);
   - roof framing gutter restoration as well as vertical ones along the walls;
   - repair of footpaths and pavements around the monastery;
   - protect the foundation against erosion and other damage;
   - drainage system development.
4. Reinforced reinforcement of the building structure:
   - use steel rods to realize the connections in the cracks formed;
   - formation of a binding between the internal cross beams and reliable steel rods under the internal masonry frame of the plasterwork;
   - use of carbon fiber reinforcement on the inside of the side walls and the apse vault spar.

Figs 19 and 20 show the main results of the analysis done with the new model.

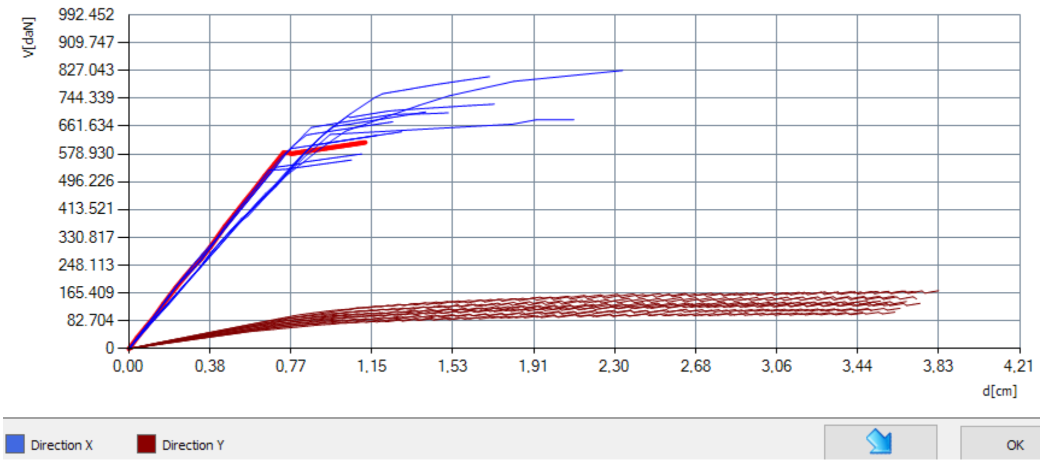

Fig. 19: Capacity curves of the church model after the structural intervention
Source: composed by the author

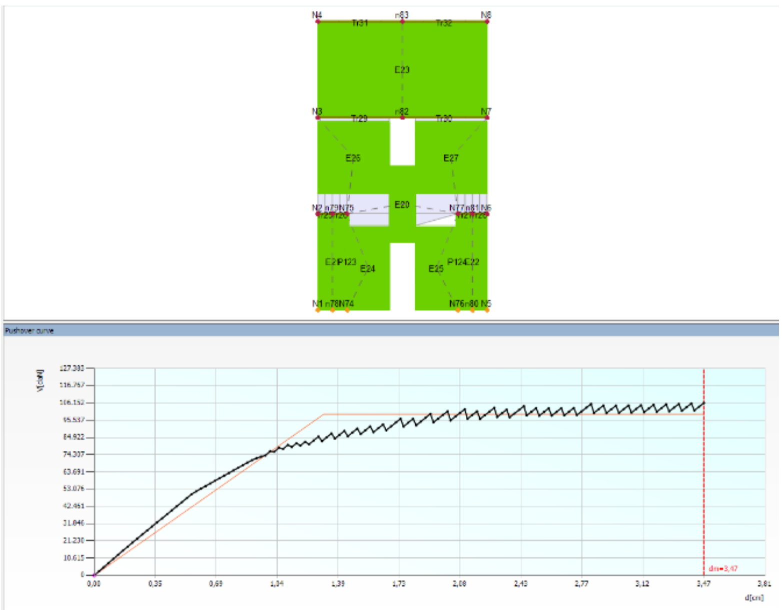

Fig. 20: Two-dimensional view of the load-bearing capacity analysis curve. The position of the panel and the nature of its behavior. (Wall at the main facade, M1). Model after structural intervention
Source: Author

After the proposed interventions, as can be seen from the analysis, the structure could become more resistant to seismic displacement and shear forces. The panels are virtually undamaged apart from the end part of the apse. Unfortunately, it is not possible to intervene in this part of the building because of the preserved frescoes on the inside of the building from different ages. Therefore, to avoid damage to them and to strengthen the masonry, it will only have low-pressure injections.

Discussion

In recent years, the issue of repairing, restoring, and renovating old cultural monuments, temples, and other buildings of historical value has been raised more frequently and more sharply. Earthquakes damage and destroy many different structures every year, so it is wise and prudent to consider methods of repairing and strengthening them. According to the United States Geological Survey (2023), only for the first five months of 2023 in the world occurred in the area of 70 earthquakes in different areas of the earthquake magnitude reached from 3.5 to 7.8 points.

To avoid damage, particularly to historic buildings, it is necessary to reinforce the supporting parts of the building in areas of high seismic activity, but many factors must be considered, such as geographical location, the susceptibility of the building structure to temporary material degradation, the interaction of different parts of the structure and so on (Babak and Shchepetov, 2018). All these and many other important factors have an impact on the types of interventions required, which makes it impossible to create a single standard for strengthening structures. However, most old buildings are built without any structural reinforcements, so they must be reinforced (Ismailova et al., 2021). Often this happens after an earthquake, the building is damaged and needs to be rebuilt and strengthened to prevent it from shifting again. For this purpose, different methods are used such as reinforcing the structure or strengthening the masonry with different injections into its joints.

Onutu et al. (2022) provide examples of methodology to determine the required interventions for restoration using the example of the Frumoasa monastery complex in Iasi, Romania. The authors rely on the results of X-ray fluorescence spectroscopy, microscopy, and petrographic approaches to determine the properties of masonry in the walls of buildings. In this research, however, modeling of the structural parts and their interactions is mostly used to determine their properties as well as the interactions between the elements with different types of masonry, for further analysis to select the appropriate structural interventions.

In the case of Rubik’s Church, although the masonry has suffered damage (cracks in the oldest part of the building), it does not require such thorough restoration. Most severely after the seismic activity of 26 November 2019, the monastery requires restoration of the plastered masonry of the apse and the wall above it, there was also definitely quite a lot of damage related to temporary material degradation such as burn-out and peeling of stones in the arches/arches of windows, doors and other connectors, the dampness problem mainly on the east side due to faulty gutters and damaged gutters that also require restoration.

Since the research aims to strengthen the masonry of the church and its structure, a qualitative determination of the required reinforcements requires an analysis of the soil and the potential seismic activity of the area (Ormeni and Daberdini, 2021). For this purpose, statistical seismology was used, based on the study of seismic activity maps and historical data, determining the seismic hazard (Pei et al., 2022; Alrubaidi et al., 2021). As it turned out, the earthquake was the strongest in the investigated area in the last century, but it does not exclude the probability of the recurrence of earthquakes with the same or bigger magnitude in the nearest future because of the possible influence of the basin. It follows that the fortified structure of the monastery should be able to withstand shocks of greater magnitude. To assess the seismic resistance, during the simulation of the church structure using structural interventions, the activity magnitude was increased to avoid repeated damage.

Using detailed plans of the Rubik’s church and with the help of thermal and surveillance cameras, it was possible to reliably identify all structural elements, masonry panel types, and other equally important features. This allowed the stiffness and strength characteristics of the masonry in the different parts of the monastery to be determined, which was then incorporated into the local modeling. The modeling itself was carried out using "3Muri" and "SeismoStruct" software to create two types of panels, with local interaction within it (stone columns (pilasters) stone wall) and without local interaction (as a homogenous macro element) to further compare their performance (stiffness) curves. Based on these local models, two full models of the whole monastery structure are created to perform local analysis and compare their earthquake resistance. For a more thorough analysis and comparison, the earthquake resistance of three different load-bearing walls, the facade-wall M1, the side wall of the structure M2, and the wall at the entrance to the apse were tested.

As described in the previous section, the behavior of both models in the longitudinal and transverse direction of the seismic action is completely different, but in both cases, the structure receives unavoidable damage. To prevent such damage in the future, the existing masonry will first need to be conserved, cleared of vegetation, restored protective coverings, and the like. Next, the masonry will require restoration, removal of old plaster, restoration of inter-masonry mortars, and covering with protective mortars (anti-frosting and anti-calcifying). Branco et al. (2021), show that lime mortars have better stability characteristics, so they should be used. The monastery also required the restoration of the roof (roof tiles), the repair of the gutters on its framework and along the walls, the repair of the paths, and the development of the drainage system at the level of the foundation.

Shabani and Kiumarsi (2022) present new methods for strengthening stone buildings and preserving them from shifts and shocks. However, in the case of the Shelbuen monastery, these methods are not feasible as they are not that widespread and not economically viable. Therefore, the classic method of structural reinforcement is used to strengthen Rubik's Church reinforcement. Reinforcement is done by creating reinforcement connections in the existing cracks to avoid their enlargement, covering the masonry with plaster with steel rods under its stone frame, creating connections of the internal bearing beams with these rods, and reinforcing the inner side of the bearing walls, and the apse vault spar with carbon fiber. By modeling the structure with the listed interventions, the seismic resistance of the monastery is significantly increased for both longitudinal and transverse seismic activity exceeding the magnitude of the earthquake. Damage can only form at one crack at the end of the apse, as full structural restorations and reinforcements are not possible in this part due to the traces of ancient frescoes preserved there.

To summarize, earthquakes can damage, and in some cases destroy, historic stone structures quite badly even now. To avoid this, more and more new methods are developed every year to strengthen them. The Rubik's Church sustained relatively little damage, but the lack of any reinforcements could affect its destruction in the event of another earthquake. A proper, quality restoration and reinforcement of the structure required an analysis of the geographical location, an analysis of the seismic activity of the area, a study of the strength characteristics of the masonry, an analysis of the interaction of the panels with different types of masonry, their modeling, and a study on earthquake resistance. This helped to determine the types of restoration and reinforcement interventions required. As it turned out, the reinforcement was sufficient to firmly reinforce the structure and avoid damage in the event of shocks/slides of magnitude greater than the strongest documented earthquakes in the study area, as evidenced by local analyses.

Conclusions

The Church of Rubik stands as one of Albania's most ancient monastic edifices, bearing profound historical significance. Its conservation, restoration, and structural reinforcement emerge as pivotal concerns in the safeguarding of the nation's heritage.

The thorough exploration of the intricate masonry techniques and irregular connections within the building is important to the research. This in-depth analysis emphasizes the necessity for accurate modeling and comprehensive assessment. By creating a behavioral model of the structure, the analysis enables a thorough examination of its capacity to withstand diverse seismic loads, guiding appropriate intervention decisions. The successful implementation of strengthening interventions, as evidenced by increased stability and minimal predicted damage in the modeled scenarios, underscores the effectiveness of the chosen strategies. Through seismic load modeling, it is predicted that the post-strengthening structure can withstand various seismic loads in accordance with established standards over its anticipated lifetime.

However, challenges in preservation persist. Certain areas, like the apse with historical frescoes, require special consideration, as complete restoration and reinforcement might compromise the original artwork. Collaboration between structural engineers and monument restoration experts is essential to ensure the preservation measures align with historical integrity. As masonry reinforcement technology advances, the demolition of ancient stone monuments can be avoided. Nevertheless, long-term impacts and timing of reinforcement strategies should be carefully evaluated to prevent unintended consequences. Continued development in reinforcement techniques, including foundations, reinforcing plasters, and other methods, is crucial to strike a balance between preserving historic structures and enhancing their structural stability.

Thus, this research underscores the significance of accurate modeling, prudent intervention choices, and interdisciplinary collaboration to safeguard historical treasures such as the Church of Rubik. It also highlights the need for ongoing innovation in reinforcement methods to secure these structures for future generations.

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