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POST-1979 MONTENEGRO EARTHQUAKE RETROFITTING OF RECTOR'S PALACE IN DUBROVNIK'S OLD CITY: PRESERVING ARCHITECTURAL AND SCULPTURAL HERITAGE

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Abstract

Building codes on earthquake-resistant design, construction, and retrofitting are being improved based on observations of building performance during strong earthquakes, with the aim of mitigating earthquake risk in proportion to the corresponding hazard. In the Republic of Croatia, prior to introduction of Eurocodes in 2005 and 2011, an example is the earthquakes M_L6.9 in North Macedonia in 1963 and M_L7.2 in Montenegro in 1979, which resulted in construction regulations in 1964 and 1981, respectively. The urban built environment was therefore constructed in compliance with building codes from different time periods, which do not provide the same level of earthquake protection as the most recent codes. Special attention is required for built heritage of outstanding significance, such as the Old City of Dubrovnik, which was included in the UNESCO World Heritage list after the M_L7.2 earthquake in Montenegro in 1979 ($I_{MCS,MAX}$ = IX–X, and of very strong intensity, i.e., I_{MCS} = VI-VII in Dubrovnik). One of the most representative buildings in the Old City is the Rector's Palace, which dates back to the 13th century but has been reconstructed several times throughout history. Due to structural damage sustained in the aforementioned earthquake, the building was comprehensively retrofitted on two occasions: 1982-1984 and 2015-2017. The objective of this study was to review the effectiveness of the retrofitted built heritage construction against contemporary design-level earthquake shaking, focusing particularly on the atrium and arcades, which are the most vulnerable structural parts of the Rector's Palace and possess significant architectural and sculptural value. The discussion will also address the structure's performance levels and provide recommendations for achieving reasonable earthquake protection within affordable means while avoiding irretrievable damage to heritage construction.

Keywords: 1979 Montenegro Earthquake, Retrofitting, Rector's Palace in Dubrovnik, Built Heritage Construction

1. Introduction

Building codes on earthquake-resistant design, construction, and retrofitting are being improved based on observations of building performance during strong earthquakes, with the aim of mitigating earthquake risk in proportion to the corresponding hazard. In the Republic of Croatia, prior to introduction of Eurocodes in 2005 and 2011, an example is the earthquakes M_L6.9 in North Macedonia in 1963 and M_L7.2 in Montenegro in 1979, which resulted in regulations in 1964 [1] and 1981 [2], respectively. The urban built environment was therefore constructed in compliance with building codes from different time periods, which do not provide the same level of earthquake protection as the most recent codes, without subsequent retrofitting. Special attention is required for historical and cultural heritage buildings of outstanding significance, such as the Old City of Dubrovnik, which was included

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in the UNESCO World Heritage list after the M_L7.2 earthquake in Montenegro in 1979 ($I_{MCS,MAX}$ = IX–X, and of very strong intensity, i.e., I_{MCS} = VI-VII in Dubrovnik). This led to the establishment of the Institute for the Restoration of Dubrovnik, which has been overseeing the retrofitting efforts.

The Old City of Dubrovnik is located in the southernmost part of Croatia, in the historical region of Dalmatia, on the eastern coast of the Adriatic (Fig. 1), at an elevation of 3 meters above sea level, at the foot of Mount Srđ. It is located in a seismically very active area, as evidenced by the Croatian Earthquake Catalogue (CEC), which records the epicentres of earthquakes throughout history, including those of the highest intensities (up to I_{MCS}=X) and the greatest values of horizontal peak ground accelerations of ground type A (a_{gR}).

a)

b)

Figure 1. Old City of Dubrovnik with the location of Rector's Palace: a) view from the southeast; b) view from the northwest (source: [3])

One of the most representative buildings in the Old City is the Rector's Palace (Fig. 2), which dates back to the 13th century but has been reconstructed several times throughout history. The Rector's Palace, located on the eastern edge of the Old City of Dubrovnik, next to the city walls and the harbour. Due to severe structural damage sustained in the aforementioned earthquake, the building was comprehensively retrofitted on two occasions: 1982-1984 and 2015-2017 [3]. The objective of this study was to review the effectiveness of the retrofitted built heritage construction against contemporary design-level earthquake shaking (e.g., 475-year hazard level), focusing particularly on the atrium and arcades, which are the most vulnerable structural parts of the Rector's Palace and possess significant architectural and sculptural value. The discussion will also address the structure's performance levels and provide recommendations for achieving reasonable earthquake protection within affordable means while avoiding irretrievable damage to heritage construction.

2. Soil and Structure Characteristics

The ground beneath the structure consists of compacted sands and clays of medium to high plasticity, extending from 13 to 27 meters to the bedrock. The groundwater level is approximately 1.5 meters below the surface and about 0.75 meters above sea level. The walls of the building are founded on strip foundations made of roughly hewn stone bonded with preserved lime-clay mortar, while the columns of the atrium are founded on stacked irregular stone fragments bound with a binder of minimal or no strength. Geotechnical boreholes in the stone foundations of the atrium columns of the Rector's Palace revealed remnants of wooden piles on which the atrium columns were supported.

In compliance with the building codes applicable during the reconstruction period (1982-1984) and according to the current building codes, the building is irregular in plan and height. The structural system of the Rector's Palace consists of three layers of masonry, predominantly with a thickness of 0.45-1.2 m. The outer layers are made of finely cut stone and lime mortar, while the central layer is composed of a larger quantity of stone rubble and fill with added lime mortar. The ceiling structures consisted originally of stone vaults and wooden joists. The vaults are made of light, porous limestone and are cross, cross-ribbed, barrel, mirrored, and combined, with a thickness of approximately 25-27 cm at the apex, with material fill up to 50 cm.

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a) b) c)

Figure 2. The Rector's Palace in Dubrovnik's Old City: a) the palace portico; b) view of the building from the southwest; c) the atrium (source: 2nd author)

The portico is located on the western facade of the building, and its construction consists of circular stone columns with Corinthian capitals on top, supporting cross-ribbed vaults. The portico, together with the entire western facade, represents the most valuable element of the Rector's Palace from a cultural-historical standpoint. The atrium extends from the ground floor to the roof height. The intermediate floor structures consist of travertine cross vaults, filled with material to floor level. The inner facade of the entire atrium is made up of columns, onto which semi-circular arches rest, except for the northern facade of the ground floor, where there are no columns, but a stone wall instead.

The roof structure of the atrium is flat, while the rest of the building contains gable and multi-gable roofs with various static systems. The roof of the western wing is gabled with a double-chair static system, the southern wing has a gabled roof with a triple-chair static system and an added column on the inner eaves, the eastern wing has a gabled corneal roof with a ridge, the southeast tower has a four-pitched roof with a presumed single-chair static system, and the roof of the northwest tower is presumed to be single-pitched.

3. History of Structural Interventions

The design of the Rector's Palace has changed throughout history, from the 13th century to the present, due to accidental actions that caused significant damage or the collapse of parts of the structure. In 1435, part of the structure was destroyed due to a gunpowder explosion and fire. The rehabilitation was completed in 1443 under the supervision of the Neapolitan builder Onofrio della Cava. The explosion in the armoury in 1463 caused the collapse of the western facade and the destruction of the second floor.

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The building was restored by the Florentine architect Salvi di Michiele. The earthquakes of 1520 and 1639 (I_{MCS} = VIII), damaged parts of the building, while the 1667 earthquake (I_{MCS} = IX–X), caused severe structural damage, but not collapse. The walls of the western facade began to tilt out of their plane, and part of the atrium collapsed. The restoration involved connecting the walls with steel ties and rebuilding the atrium. The first documented retrofitting including repairs and addition of steel ties, was completed in 1704. In 1843, steel ties were installed to support the western facade, along with several rough construction interventions that disrupted the building's structural system. Due to the poor condition of the building, improvement efforts were made in 1952, including relieving the terrace around the atrium, restoring the roof structure, and structure strengthening. The 1962 M_L=5.9 earthquake near Makarska (Croatia) and the 1968 M_L=5.5 earthquake on the Montenegrin coast highlighted that the safety of the Rector's Palace was once again at risk. As a result, in 1968, investigative work was initiated by the Dubrovnik Institute for the Protection of Cultural Monuments, aiming to assess the building's condition. The 1979 Montenegro earthquake, caused structural damage to the Palace. The walls separated from the ceiling structures, cracks appeared in the vaults, and additional tilting of the walls of the western facade occurred, with the wall tilting 23 cm from the vertical. The Palace was given priority in the restoration, and in 1981, the main restoration project was developed, with the works commencing in 1982.

3.1. Structural Interventions 1982-1984

The restoration began in 1982 and was completed in 1984 (Fig. 3) [4], in compliance with the building code [2], and conservation requirements. The masonry strip foundations were strengthened by adding reinforced concrete beams measuring 30/80 cm alongside them, connected by steel anchors (d=20 mm). In the atrium, reinforced concrete beams were installed on both sides of the existing foundations of the stone columns. Stone walls were reconstructed in locations where they had been removed in 1843, while several partition walls were demolished. Two structural walls were reinstated on the ground floor, mezzanine, and first floor. Steel anchors along the full height of the wall-ceiling connection lines were added. The walls were interconnected with reinforced concrete slabs and/or diagonal steel ties at three levels: at the foundation level, at the mezzanine ceiling level, and at the first-floor ceiling level. The atrium was reinforced at the mezzanine ceiling level with a system of perpendicular steel ties. At the first-floor ceiling level, reinforced concrete slabs were installed in the towers, similar to the mezzanine ceiling level. Between the towers on the western façade at the first-floor level, there is a space without structural walls perpendicular to the façade. To prevent further tilting of the façade out of its plane, a very rigid diaphragm was constructed. The strengthening at the first-floor level created a closed ring of reinforced concrete ties, connecting all four wings of the building with the atrium. An expansion joint was constructed between the Rector's Palace and the City Hall, except in the south-eastern section, which was omitted due to heritage sensitivity, and the eastern wing, where structural ties to the city walls made it unfeasible.

a) b)

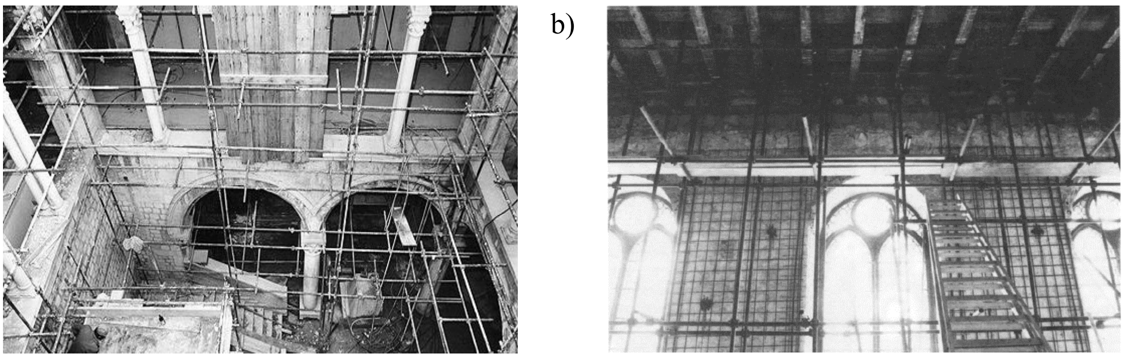

Figure 3. Rehabilitation of the Rector's Palace Following the 1979 M_L=7.2 Montenegro Earthquake a) atrium; b) inner spaces (source: [3])

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3.2. Structural Interventions 2015-2017

Due to the appearance of numerous cracks in the atrium, construction work began at the end of 2015 and was carried out in three phases [3]:

1) the structural rehabilitation of the foundations and the sub-foundation zone of the atrium. Additionally, the first phase included the structural rehabilitation of the foundations and the sub-foundation zone of the atrium, preceded by investigative works using probes and boreholes. The results of these investigations did not align with the design assumptions, as the load-bearing rock was found to be at a greater depth than anticipated. The foundations were strengthened using load-bearing micropiles, secondary piles, and the grouting of the space enclosed by micropiles beneath the isolated footings, resulting in a compact foundation body supporting the ground-floor columns of the atrium. Full-scale 1:1 model testing of the ground-floor and upper-floor columns under actual loading conditions was also conducted.
2) the structural rehabilitation of the stone columns on the ground floor and the paired columns of the north façade on the upper floor, the installation of ties at the springing points of the vaults, and the completion of work on the roof terrace.
3) the rehabilitation of the stone paired columns of the east, west, and south façades on the upper floor, the installation of ties at the springing points of the upper-floor vaults in the atrium, the paving of the atrium ground floor, and the remaining conservation and restoration works.

The retrofitting performed in the atrium are of a local nature, meaning they improve the seismic performance of the atrium but not the building as a whole.

4. Characteristics of construction materials

The construction materials of the built heritage in the Old City of Dubrovnik, and generally along the eastern Adriatic coast, consist primarily of high-quality processed limestone blocks obtained from nearby quarries, bonded with lime mortar (see Fig. 4).

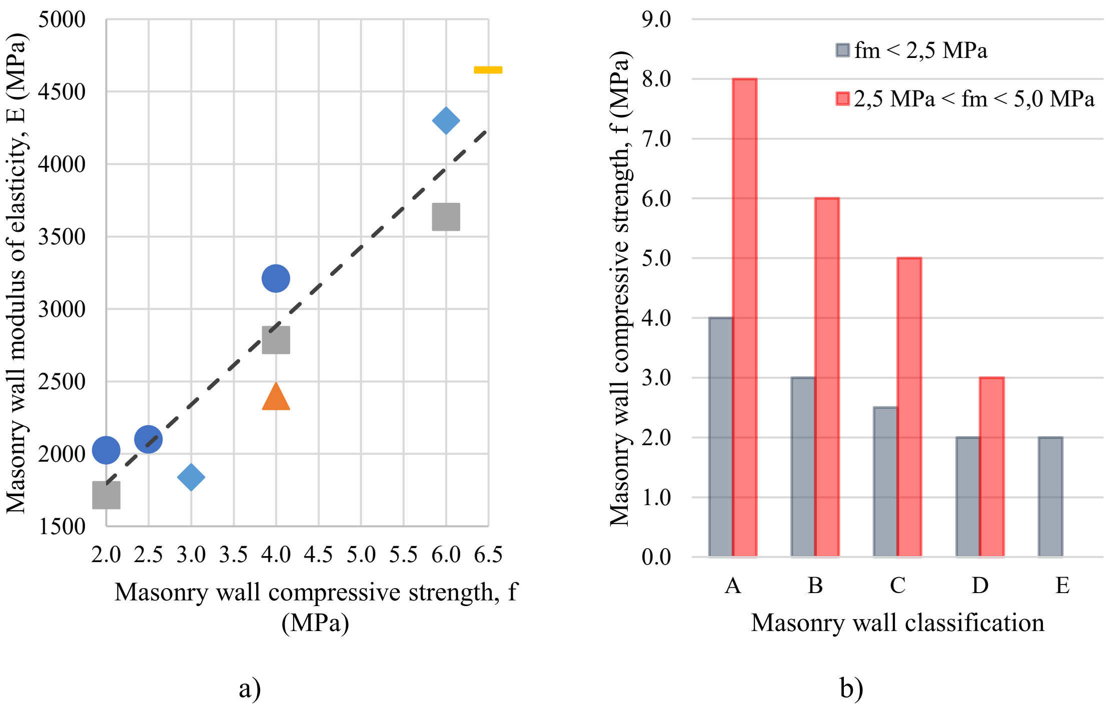

Figure 4. Material characteristics of stone masonry units and walls belonging to eastern Adriatic coast: a) unit and wall compressive strength relation; b) wall classification and compressive strength relation [5]

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The wall classification (A-E) in Figure 2b. as proposed by [5] where letter symbols refer to: A designates walls made of finely dressed and properly arranged stone blocks, without intermediate layers; B walls made of large regularly dressed stone blocks with a relatively narrow central layer filled with fill material and stone chippings; C walls made of large irregularly dressed stone blocks with a relatively narrow central layer filled with fill materials and stone chippings; D walls made of roughly dressed irregular stone blocks with a large quantity of stone chippings and fill material in the central layer, and with irregular joints; E walls made of undressed stone with a large quantity of fill. Other materials used are wood and steel (ties), and a concrete class of C25/30 was assumed (retrofitting).

5. Vibrational characteristics of the building

Measurement of ambient vibrations at the Rector's Palace was conducted in 1981 (on the damaged building) and in 2023. The 1981 measurements recorded values of 0.36 s for the north-south direction and 0.37 s for the east-west direction for the first mode of vibration. In the 2023 measurements, repeated at the same locations as in 1981 with additional measurements around the atrium, values of 0.30 s were observed for both the north-south and east-west directions. Period values of 0.34 s were determined near the atrium. More details on the measurement process and the obtained data are available in [6–8] and are omitted from this report for brevity.

6. Spatial FEM Model of Rector's Palace

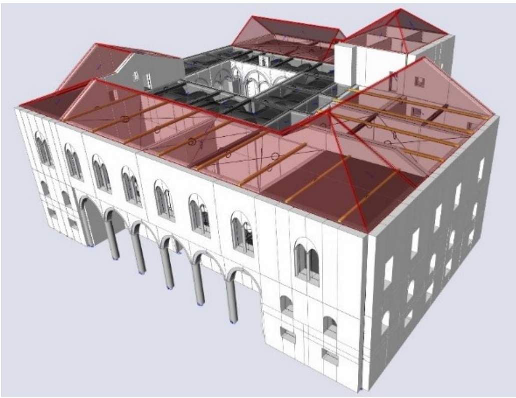
6.1. Development of the Structural Model

The spatial structural FEM model for simulating the seismic behaviour of the Rector's Palace was created using the SCIA Engineer 22.1 [9] software, based on architectural and 3D scans of the Rector's Palace (see Figs. 5 to 9). The walls were modelled as 2D "Wall" elements, columns as 1D "1D Member" elements, and vaults as 2D "Shell" elements. The roof was not modelled, and the load was applied to the walls of the upper floor. The connection between the walls and the foundation soil was simulated using linear pinned supports, while point supports were used for the columns. Displacements were constrained at the locations where the Palace connects with the Old City walls and adjacent buildings.

In the second model, applied were the strengthening measures of the 1982-1984 restoration (see Sec. 3.1). A dilation joint was also added to the northern part of the Palace. The reinforced concrete slabs were modelled as 2D "Plate" elements, steel ties and horizontal ring beams as 1D "1D Member" elements, with only the transverse ring beams modelled, while the longitudinal ones were applied as loads on the model.

The third model refers to the state of the building after the reconstruction carried out between 2015 and 2017. At the locations of missing ties in the atrium on the ground and upper floors, steel ties were added to the spring points of the vaults, modelled as 1D "1D Member" elements.

a)



b)

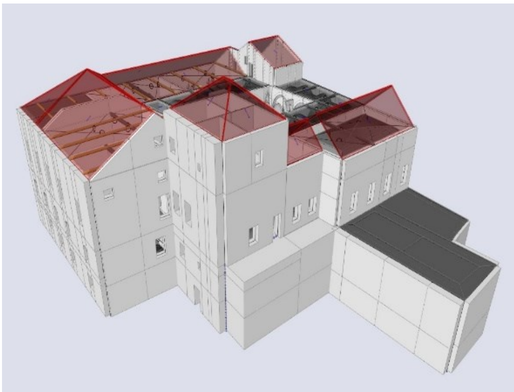


Figure 5. Finite Element Method (FEM) spatial model of Rector's Palace: a) view from the southwest; b) view from the southeast [8]

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Ground floor | Mezzanine | First floor

a) b) c)

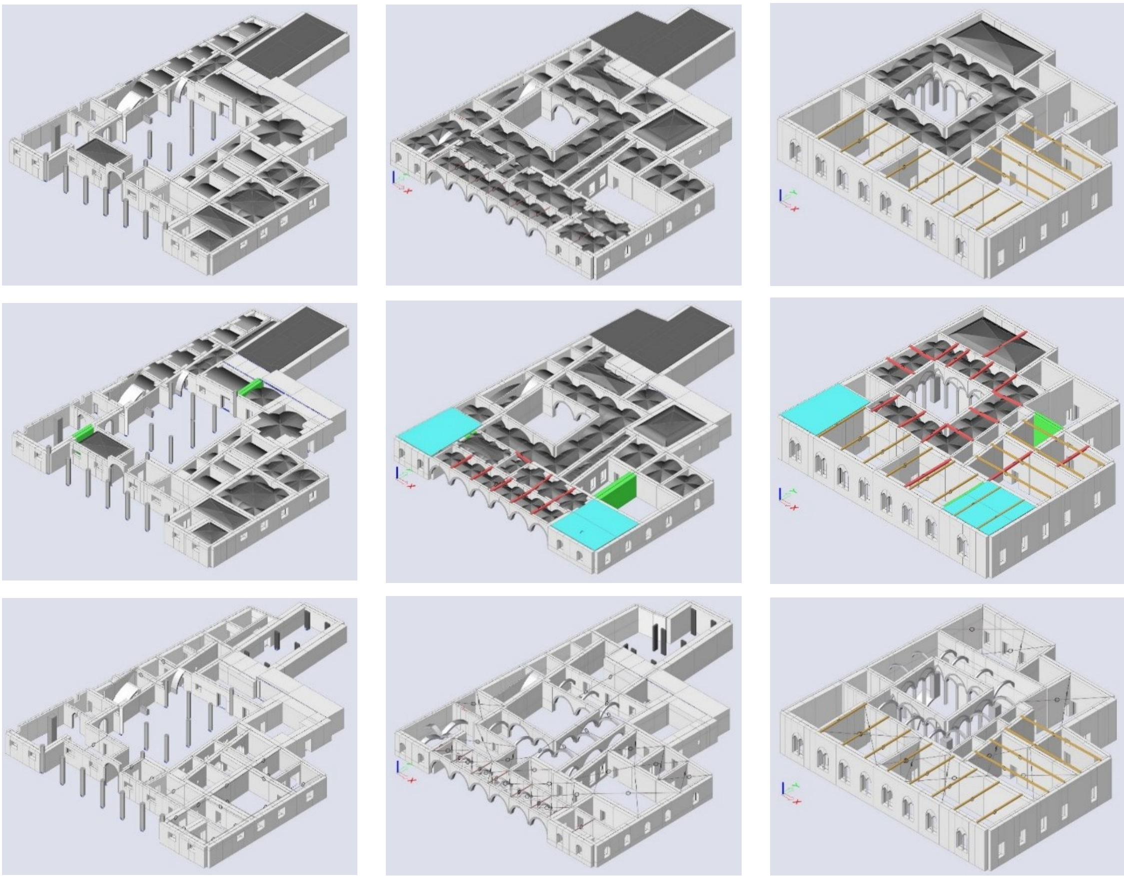

Figure 6. Retrofitting of Rector's Palace – pre-1979 earthquake and post-1982-1984 interventions: a) condition prior to the 1979 earthquake; b) condition after the 1982–1984 restoration, including: stone walls (green), reinforced concrete slabs (cyan), and horizontal tie beams (red); c) connection of stone walls with steel ties during the same period (shown separately for clarity) [8]

a) b)

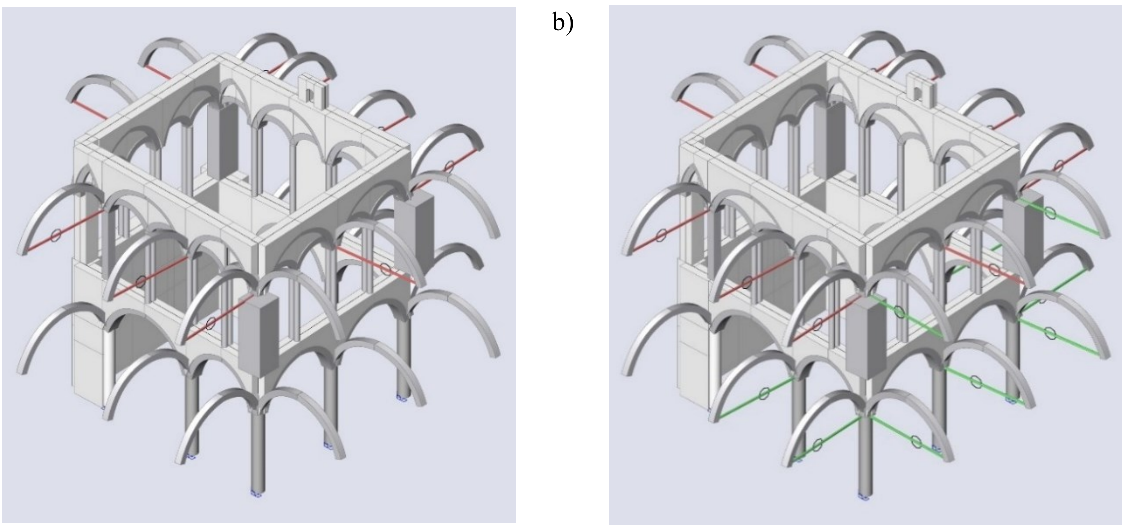

Figure 7. Retrofitting of Rector's Palace Atrium Completed in 2015–2017: a) condition before and after the 1982–1984 restoration with the existing steel ties at the atrium floor level (red); b) condition after the 2015–2017 restoration with the newly installed steel ties at the springing points of the atrium cross vaults (green) [8]

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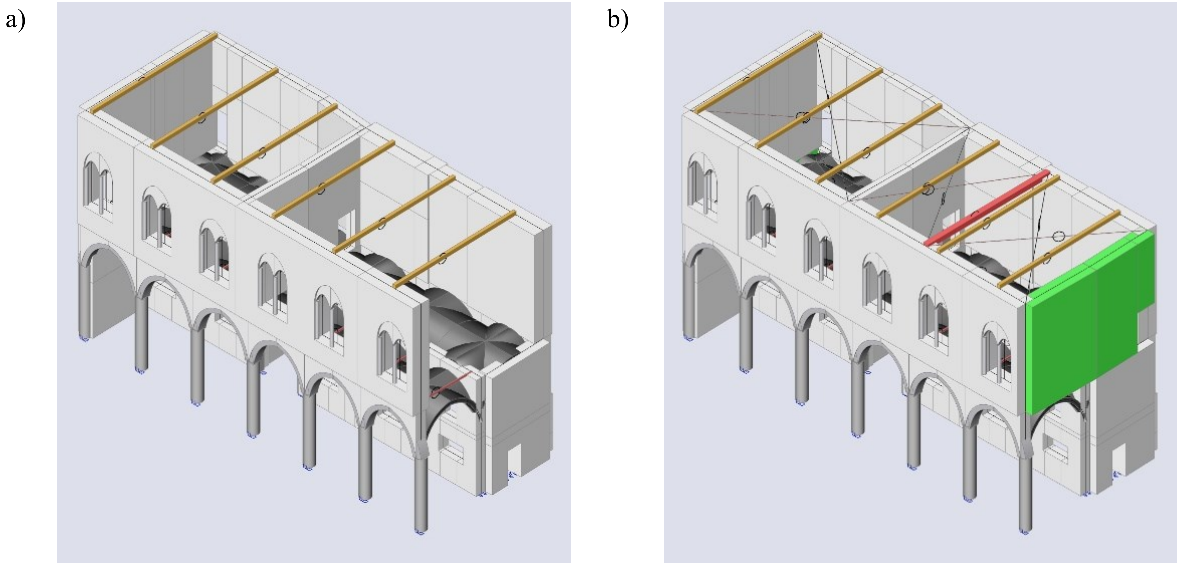

Figure 8. Portrayal of the west facade portico in the structural model: a) before and; b) after the 1982-1984 restoration [8]

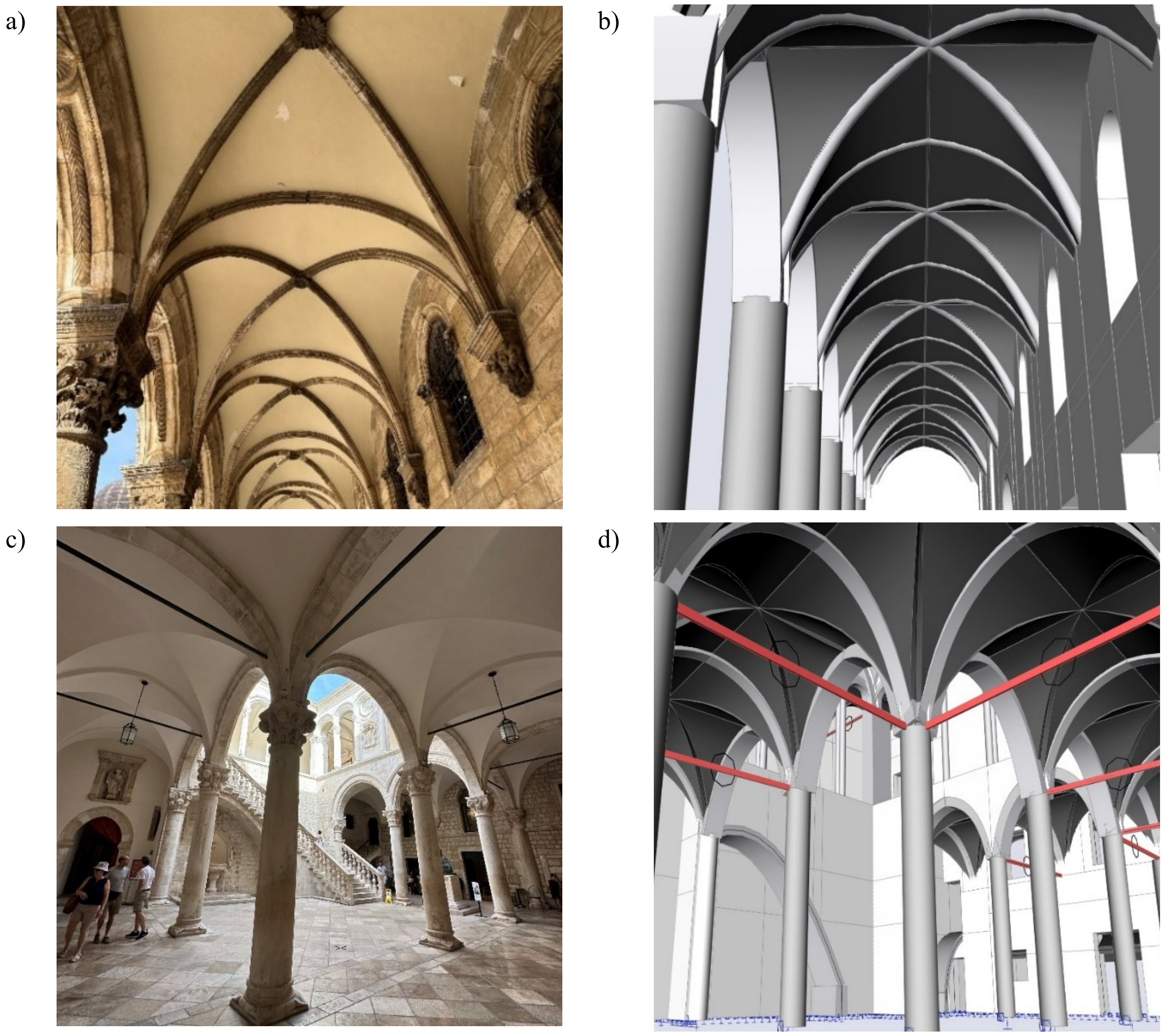

Figure 9. Representation of the structure in reality and in the computational model: a) ribbed cross vaults of the arcade; b) cross vaults of the atrium [3,8]

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6.2. Actions on the structure

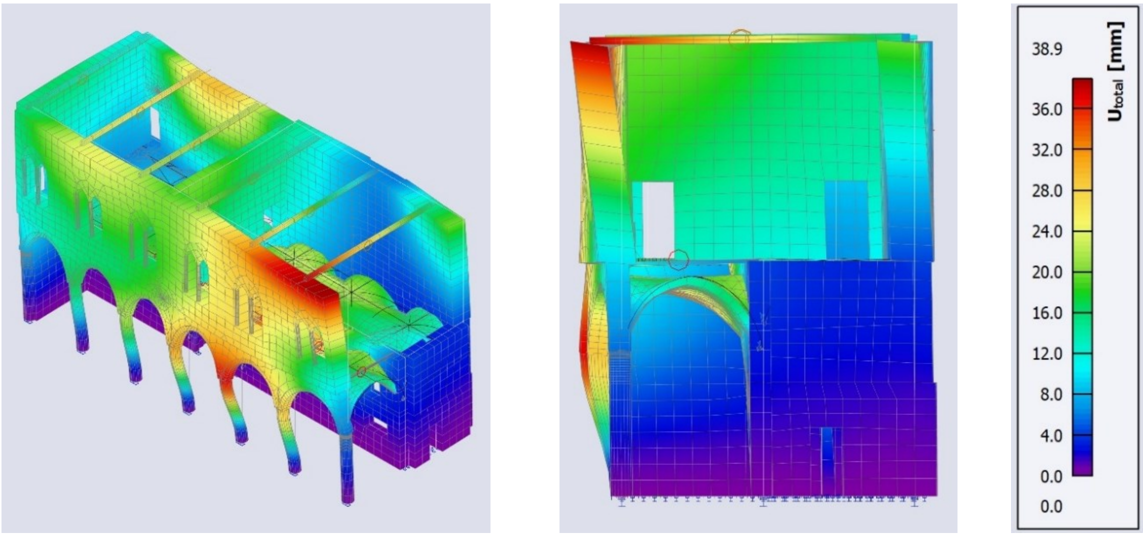
The following actions on the structure were considered: permanent (G), variable (Q), and accidental action (A) [10–14]. The self-weight of the stone walls at 25 kN/m³, the embankments above the vaults (fill material and floor layers) at 14 kN/m³, wooden beams (wooden structure and floor layers) at 8 kN/m³, and the roof structure (wooden structure and tiles) at 5.8 kN/m³ were adopted. The Rector's Palace falls under the C3 usage category, so the floor load for intermediate floor structures is taken as 5 kN/m³, and for the roof over the atrium (slope < 20°), based on the H usage category, the floor load is 0.75 kN/m³. Snow load is neglected due to the very small values of the load on the building's roof structure, as well as wind load, which has no impact on massive masonry structures. Seismic action was considered using the design response spectrum for a return period of 475 years (10% exceedance probability in 50 years), as well as the response spectrum for the actual 1979 Mne earthquake recorded at Herceg Novi station. A Type 1 response spectrum with a damping ratio of 0.05 was used. According to [15], soil type B was assumed for the location of the Rector's Palace. The peak ground acceleration for soil type A at a return period of 475 years for the city of Dubrovnik is 0.30g, the importance factor for the selected building was 1.2, and the behaviour factor 1.5. Non-seismic and seismic combinations of actions were considered as shown in Table 1. Due to the brevity and purpose of the study, only the seismic combinations of actions and their results are presented.

Table 1. Seismic combination of actions considered (the x-axis is parallel to the western façade, extending in the north-south direction; the y-axis is extending in the east-west direction)

No.	Seismic combination of actions	Rspns. spectr.
1	$G + E_{Ed,x} + 0,30 \cdot E_{Ed,y} + \sum \Psi_2 \cdot Q$	EN1998-1
2	$G + 0,30 \cdot E_{Ed,x} + E_{Ed,y} + \sum \Psi_2 \cdot Q$	
3	$G + E_{Ed,x} + 0,30 \cdot E_{Ed,y} + \sum \Psi_2 \cdot Q$	1979 Mne eq.
4	$G + 0,30 \cdot E_{Ed,x} + E_{Ed,y} + \sum \Psi_2 \cdot Q$	

7. Outcomes of the analysis

Outcomes of the analysis are shown in form of spatial displacements in Figs. 10 & 11.



a)

Figure 10. Portrayal of the west facade portico in the structural model: a) before and; b) after the 1982-1984 restoration

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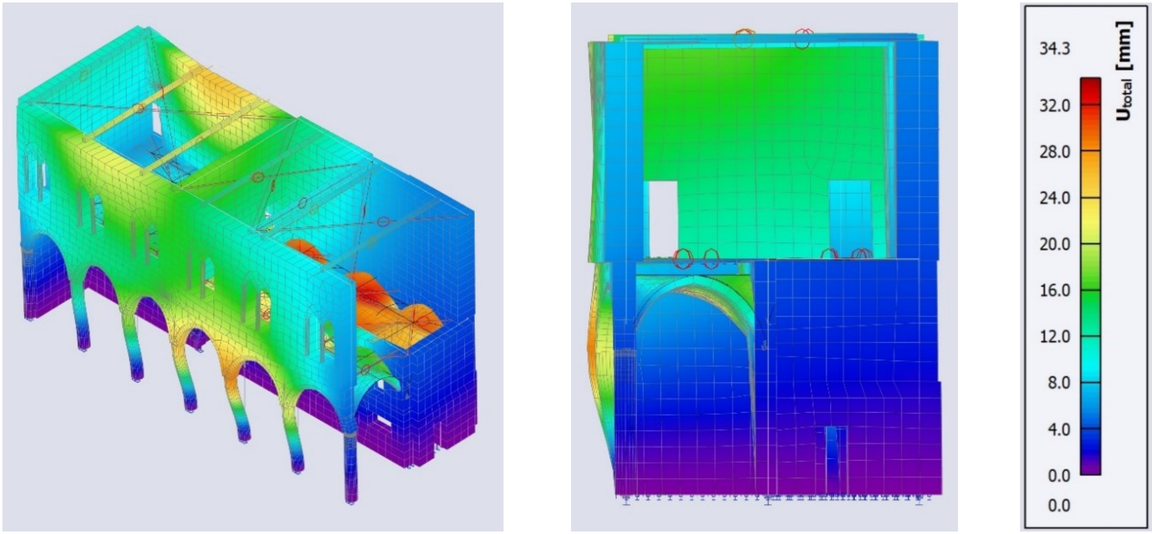
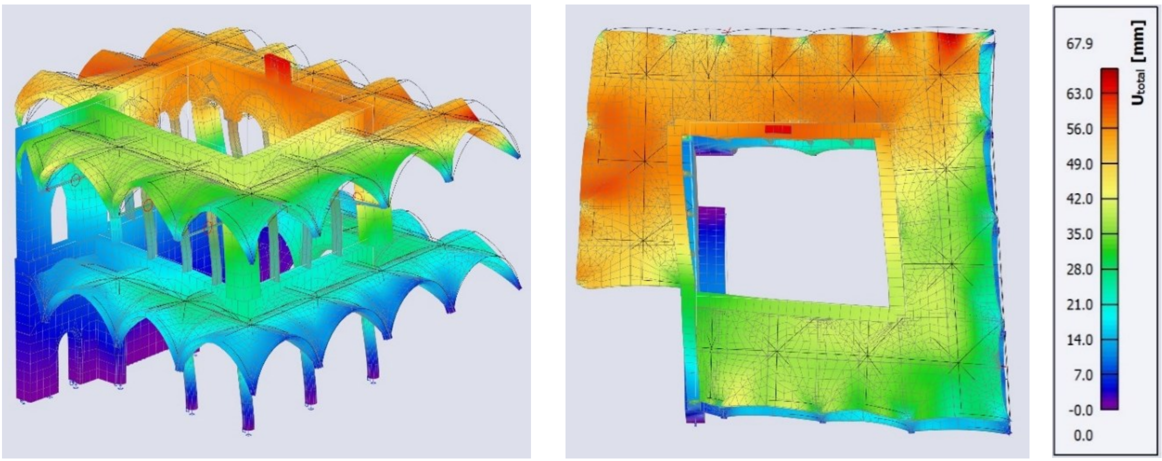
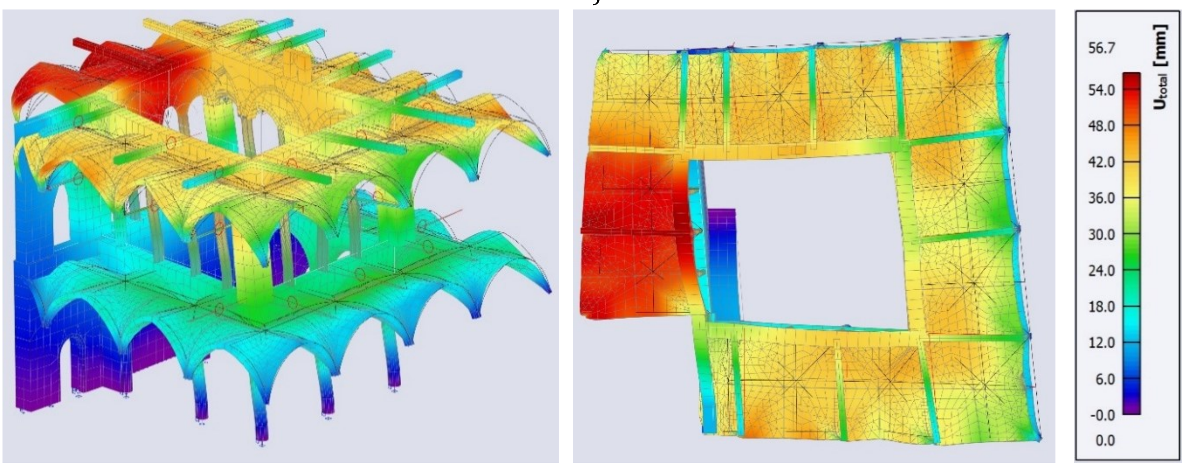


b)

Figure 11. *continuation …*



a)



b)

Figure 11. Spatial displacements of the atrium for seismic combination of actions no. 3: a) before 1982-1984 restoration; b) after the 1982-1984 restoration; c) after 2015-2017 restoration

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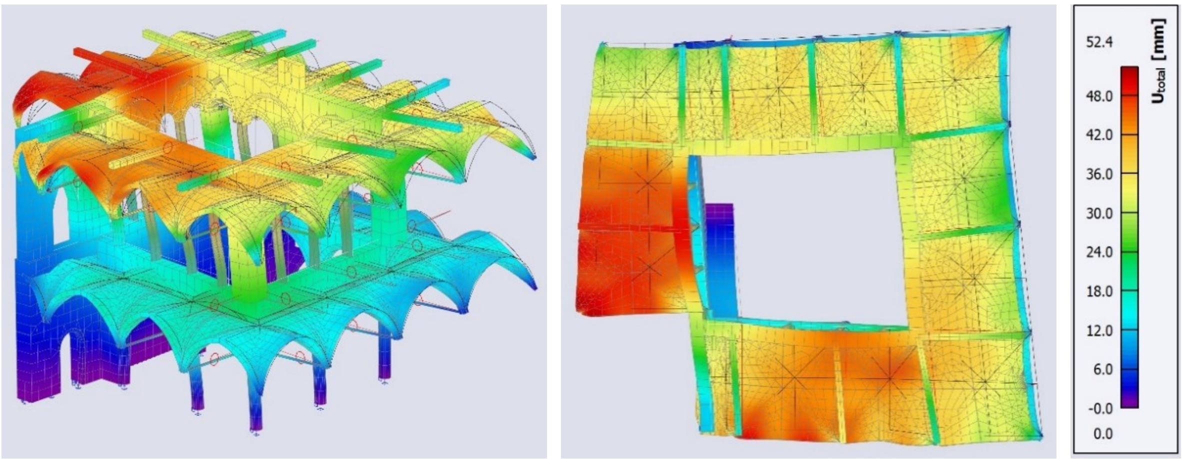

c)

Figure 12. *continuation …*

By conducting a sensitivity study of the finite element mesh, a mesh density of 0.5 m was adopted. Comp. model was calibrated against first natural period from 1981 measurements (see Sec. 5). A modal analysis, i.e., the analysis of natural vibrations of the Rector's Palace, was conducted for the first six vibration modes across three computational models. For the measured vibration period of 0.37 s, a mean elasticity modulus of 1750 MPa for the B-grade walls was adopted for the entire building. Figs. 1 & 2 illustrate the spatial displacements for the most unfavourable seismic combination, i.e., combination no. 3, as outlined in Table 1.

8. Conclusions

The monumental heritage of the Old City of Dubrovnik, constructed with stone, generally does not meet the design criteria and construction standards for earthquake-resistant buildings in compliance with EN 1998-1:2004 and EN 1996-1-1:2005 codes. The assessment of Rector's Palace was conducted by means of a computational model on both global and local levels (atrium and arcades) for non-seismic and seismic combinations of actions, supported and calibrated with field measurements and laboratory tests. Seismic combinations with the response spectrum of the 1979 M_L=7.2 Montenegro earthquake, resulted in higher spatial displacements, as compared to those with the EN1998-1 design spectrum for a return period of 475 years.

In the global analysis, seismic combinations with dominant earthquake action in the x direction cause the largest spatial displacements in the atrium area, while for the dominant y direction, the greatest values occur at the wall above the arcade on the western façade, where the wall is missing. With the addition of reinforcement, the building deforms the most in the atrium area for both seismic directions. Displacements in the atrium vaults are reduced due to the transverse horizontal tie beams in the post-1982-1984 restoration model and the tie rods at the vault spring points in the post-2015-2017 restoration model, as well as on the western façade due to the high effectiveness of the reinforced concrete slab reinforcement and the horizontal tie beams and rods system.

In the local analysis, retrofitting lead to a reduction in displacements, which coincide with the tilt points of the western façade wall following previous earthquakes. The atrium deforms the most in the eastern wing during the seismic combination with dominant action in the x direction, while in the y direction, larger displacements occur in all four wings. With the addition of strengthening, the western and eastern parts of the atrium on the upper floor experience the greatest deformations due to the lower degree of lateral support of the walls compared to the eastern and southern wings, where there are no transverse structural walls to stiffen the supporting walls of the vaults.

A detailed study of the seismic performance of the arcades is recommended due to the proposed implementation of additional strengthening.

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