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The Effects of Strong Earthquakes on Built Heritage: A Preliminary Case Study of Rector's Palace in Dubrovnik's Old City

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Abstract: The Old City of Dubrovnik's historical urban heritage architecture, consisting of poorly to well-built irregular stone masonry construction, is at high risk of earthquakes. It was enlisted as a UNESCO World Heritage after the severely damaging 1979 M_w = 7.1 Montenegro earthquake. Retrofitting strategies to a certain degree of earthquake protection have been made to the monument heritage architecture after repeating destructive earthquakes for several centuries. The originally 13th-century Rector's Palace underwent several major modifications throughout history after disastrous events: fire in 1435, a gunpowder explosion in 1463, and earthquakes in 1520, 1667, and 1979. The design and construction information were collected from historical records and studies performed by various researchers, including field measurements and laboratory tests. Based on the data gathered, the building's resistance to destructive earthquakes in compliance with contemporary building codes was determined using simulations on a calibrated spatial structural model. The study revealed that the building's critical parts are most susceptible to a certain degree of damage or even collapse. The presented case study is the basis for decision-making and implementing the building's earthquake risk reduction measures. Additionally, it will serve as a guide for earthquake risk evaluation on similar buildings, even though they may differ in degree or detail.

Keywords: Rector's Palace; Old City of Dubrovnik; heritage architecture; stone masonry construction; destructive earthquakes; retrofitting; earthquake performance

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1. Introduction

The destructive M_w = 5.3 and M_w = 6.4 earthquakes that struck Croatia in 2020 [1–4] not only caused significant physical damage to buildings and loss of life [5,6] but also posed a grave threat to the country's rich cultural heritage assets [7–10]. By drawing insights from these events that shed light on the consequences of earthquakes on heritage preservation efforts and the measures taken to mitigate such risk, the vulnerability at both urban and single asset scales in the Old City of Dubrovnik (see Figure 1) was explored to subsequent exposure, i.e., the effect of destructive earthquakes. The Old City is enlisted as a UNESCO World Heritage Site [11] after a very destructive 1979 M_w = 7.1 Montenegro earthquake of extreme intensity in the vicinity of the epicenter, i.e., $I_{MCS,MAX}$ = IX–X, and of very strong intensity, i.e., I_{MCS} = VII in Dubrovnik. The earthquake damage report indicated that 1071 registered cultural heritage assets suffered considerable damage (see Figure 2). In compliance with the Croatian Earthquake Catalogue (developed in 1996 [12] and continuously updated), the Old City of Dubrovnik was exposed to past significant earthquake events, namely: heavily damaging, i.e., I_{MCS} = VIII earthquakes in 1520 and 1639, destructive or heavily destructive, i.e., I_{MCS} = IX–X earthquake in 1667. The consequences of the latter, also known as the "Great Dubrovnik Earthquake", are in the rank of the 1775 Lisbon, Kingdom of Portugal, and the 1908 Messina, Kingdom of Italy, earthquakes [13].

(a)

(b) (c)

Figure 1. Old City of Dubrovnik: (**a**) a view of the city from the southeast; (**b**) a street view in the residential part with the former Jesuit College in the distance; (**c**) a street view of City Hall, Rector's Palace and the Cathedral (courtesy of the Institute for the Restoration of Dubrovnik [14]).

The urban historical heritage architecture in the Old City consists of residential and public buildings, among which are the monumental buildings of outstanding significance and value, such as, e.g., Rector's Palace, Sponza Palace, City Hall, Jesuit College, etc. (see Figure 3). The categorical weakness of built heritage, with reference to the seriousness of destructive earthquake occurrence, is in its (irregular) construction comprising massive unreinforced natural stone masonry of different quality of wall texture (including the confining fortification ramparts, i.e., walls). In addition, they were built with poor lime mortar, and with the floor structures comprised of wooden joists, masonry vaults, arches, and domes with an inadequate inter-connection with the rest of the structure, which is unsuitable for areas of high seismicity (highest in Croatia [15]), where the city is located.

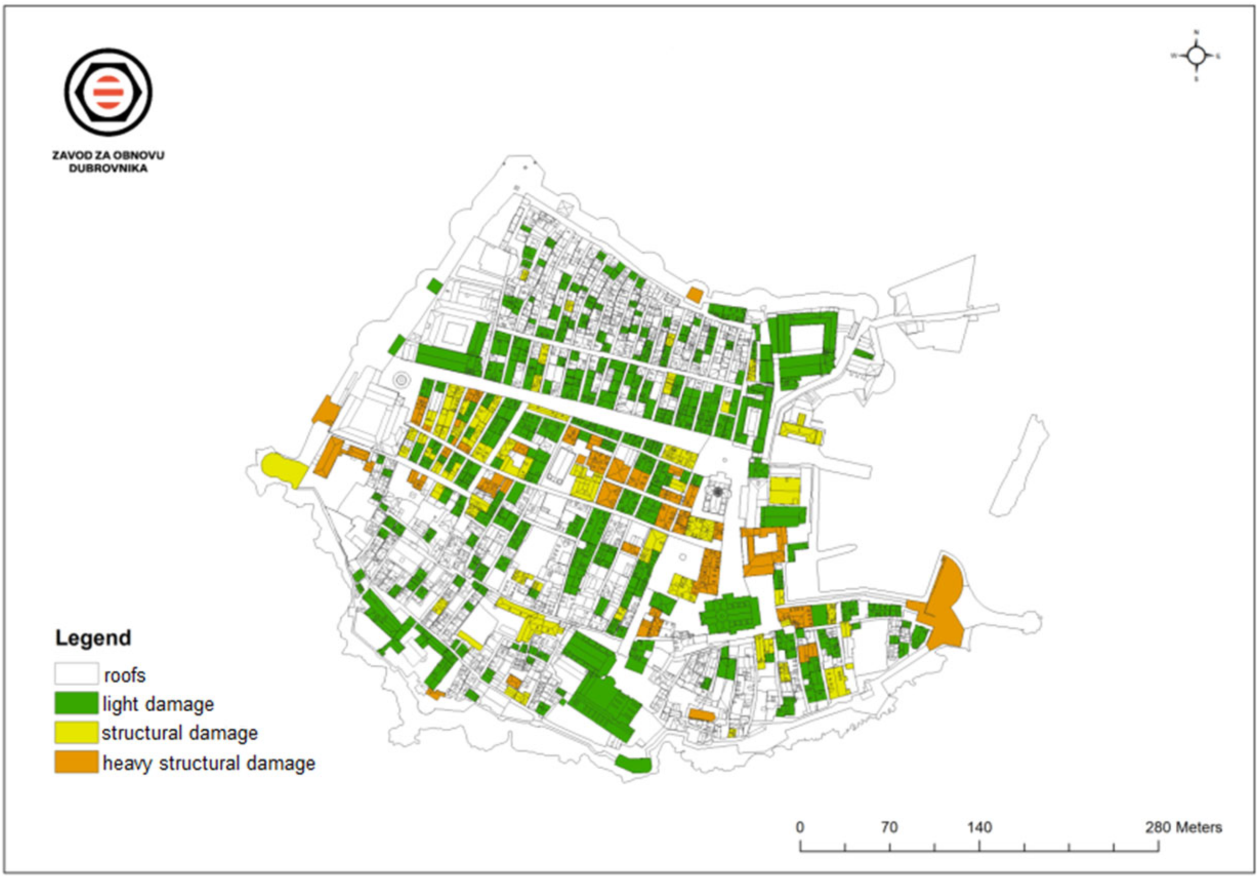


Figure 2. Map of the Old City of Dubrovnik showing the grade of damage to buildings after the very destructive 1979 M_w = 7.1 Montenegro earthquake of very strong intensity, i.e., I_{MCS} = VII measured in the city (legend by color: white = negligible to slight damage; green = moderate damage; yellow = substantial to heavy damage (structural damage); red = very heavy damage or destruction) (publicly available at URL: https://zod.hr/obnova-dubrovnika/potres-1979-i-aseizemicka-sanacija/; accessed on 2 June 2023).

In order to adequately regulate and conduct the restoration program (strengthening or replacement) and to gather the necessary and substantial financial resources required, a package of laws and regulations was enacted [16–21], among which was the establishment of the Institute for the Restoration of Dubrovnik in 1979 [14]. The ongoing restoration (1979–present day), interrupted by the war in Croatia (1991–1995), included various experts, such as civil engineers, geologists, seismologists, architects, art historians, surveyors, archeologists, and others, due to the considerable difficulty and complexity of the problem. The restoration (retrofitting) effort (1979–1989) and 1996–present-day referred to building codes of the period such as [22] 1981–1999 and [23] 1999–2012, which, if compared to contemporary construction in compliance with [24,25] could provide 30–50% or 70–100% of required earthquake resistance, respectively. The retrofitting strategies employed, in general, consisted of the removal, replacement, or addition of RC walls in critical places, the execution of horizontal confining elements and RC slabs, and the addition of steel tie rods or steel bracings.

Figure 3. Map of the Old City of Dubrovnik showing the retrofitted historical monumental buildings before 1989 (colored in blue) after the very destructive 1979 M_w = 7.1 Montenegro earthquake of very strong intensity, i.e., I_{MCS} = VII measured in the city (publicly available at URL: https://zod.hr/obnova-dubrovnika/potres-1979-i-aseizemicka-sanacija/; accessed on 2 June 2023).

Based on the comprehensive data gathered, including the recent experimental and theoretical scientific laboratory and field research, the historical monument Rector's Palace's performance to destructive earthquakes in compliance with contemporary building codes [24,25] was determined using simulations on a calibrated spatial structural model through a finite element macro-modeling approach and the response spectrum analysis.

Considered were the site [26] and seismic hazard characteristics [11,12,15] in the region, building classification (vulnerability class B in pre- and C in post-retrofitting design condition in compliance with EMS-98 [27] and fragility concepts [28,29]), its structural characteristics, and the contemporary building code requirements [24,25,30].

The study indicated that the building's critical parts were the most susceptible to some degree of damage or collapse, which coincided with the building's damage survey after past earthquakes (e.g., 1979 M_w = 7.1 Montenegro earthquake) and its measured vibrational characteristics. A similar approach to historical (masonry) buildings, as compared to other methods, e.g., [31,32], has been exercised by [33–37] and supported by the conclusions of [38]. The presented preliminary case study, conducted in the framework of the Croatian Science Foundation Research Project IP-2020-02-3531 Seismic Risk Assessment of Cultural Heritage Buildings in Croatia, due to the building's complex architecture, as well as the design and construction approach [39], is the basis for the further detailed analysis, decision-making, and implementation of the building's earthquake risk reduction measures. Additionally, as a result of numerous building constructions, it will serve as a guide for earthquake risk evaluation on similar buildings in Dubrovnik's Old City, even though they may differ in degree or detail (e.g., former Jesuit College building [37]).

The main objectives and contributions of this study are the following: (a) to assess and compare the earthquake performance and vulnerability of a UNESCO-listed cultural heritage building, namely the Rector's Palace in Dubrovnik's Old City, in its pre- and post-retrofitting (1982–1984) design condition, i.e., survivability, by means of a finite element macro-modelling approach and response spectrum analysis; (b) to gather and classify the relevant mechanical characteristics of stone masonry buildings in the observed region, with regard to locally available historical materials used and the craftsmanship of their construction by considering the laboratory tests and available literature; (c) to validate the building's post-retrofitting design conditions with reference to contemporary building code earthquake performance (and vulnerability) requirements, thus indicating the building's critical parts most susceptible to a certain degree of damage or even collapse; and (d) to emphasize the importance of testing the historical masonry building's dynamic properties in the process of structural macro-model calibration in order to support their global assessment to destructive-earthquake-related risk.

The novelty of this study is in providing insight into the effectiveness of the retrofitting measures implemented in a particular cultural heritage stone masonry building in Dubrovnik's Old City after a very destructive 1979 M_w = 7.1 Montenegro earthquake in the period from 1982 to 1984 with reference to contemporary building code requirements and the building's pre-retrofitting design condition.

The overall aim is to find an affordable means of avoiding irretrievable damage to heritage structures in design-level earthquake shaking, e.g., 475-year hazard level [40–42]. Achieving this would not only be of great value to Dubrovnik City, i.e., owners of property subjected to destructive earthquakes, but could also make an important contribution to the sustainability of the built heritage [43,44], a matter of great importance to the community and its identity [45,46].

This study is organized in the following manner. The earthquake-related risk and damage to the built environment of Dubrovnik's Old City and the risk reduction measures are presented in Section 1. The overview of the historical urban development of the Old City, defining its architectural, art, and historical significance and value as a UNESCO cultural heritage, is described in Section 2. Section 3 describes the design, construction, and retrofitting of Rector's Palace, while Sections 4 and 5 provide information on the building's construction materials and vibrational characteristics, respectively. Section 6 is about the structural assessment and performance of the Rector's Palace with reference to contemporary building code requirements, i.e., earthquake demands, accompanied by a discussion in Section 7. Section 8 summarizes the main objectives and findings of the study, with indications for future work.

2. Historical Urban Development of the Old City

The Old City of Dubrovnik (lat. *Ragusium*), a trade and port city located in the southernmost part of Croatia (in the historical region of Dalmatia), on the eastern coast of the Adriatic, was founded in about 615. It consisted of two settlements separated by shallow sea embayment, i.e., the one built on the mainland with a Slavic population named *Dubrava* and the other named *Ragusium* with a Latin (Roman) population. The settlements merged by embanking the embayment, what today represents the main city street named *Stradun*. The city was named *Dubrovnik* by its mainland settlement.

The city was under the suzerainty of the Byzantine Empire (615?–1205) and Venice Republic (1205–1358) till the foundation of the historically famous sovereign state Republic of Ragusa (1358–1806/8). It permanently lost its sovereignty under the French Empire and the Kingdom of Italy (1806–1815). Afterward, it became a part of the Triune Kingdom of Croatia, Slavonia, and Dalmatia, i.e., Austrian (1815–1867) and Austro-Hungarian Empire (1867–1918). The Yugoslavian period (1918–1991) lasted up to the declaration of independence of the Republic of Croatia (formerly one of the Socialist Republics of Yugoslavia), to which it belongs up to this day. The Republic of Ragusa is historically famous for its notable achievements in diplomacy and maritime trade, as it is considered one of the major ports and trade routes in the Mediterranean between the Levant and the rest of Europe, reaching even up to India and the United States. This was particularly pronounced during the Ottoman suzerainty (1451–1684), where it had exclusive trade rights, protection, and safety by the Ottomans within the Empire, therefore being a competitor to the Republic of Venice. The motto of the Republic was *Non bene pro toto libertas venditur auro*, which translates to *Liberty is not sold for all the gold in the world*.

The Old City, confined with stone masonry fortification ramparts, is a unique urban entity that successfully preserved its historical form and meaning. In compliance with the contemporary urban plan (see Figure 4), the city comprises residential and public buildings. The buildings were adapted to the contemporary requirements according to their purpose.

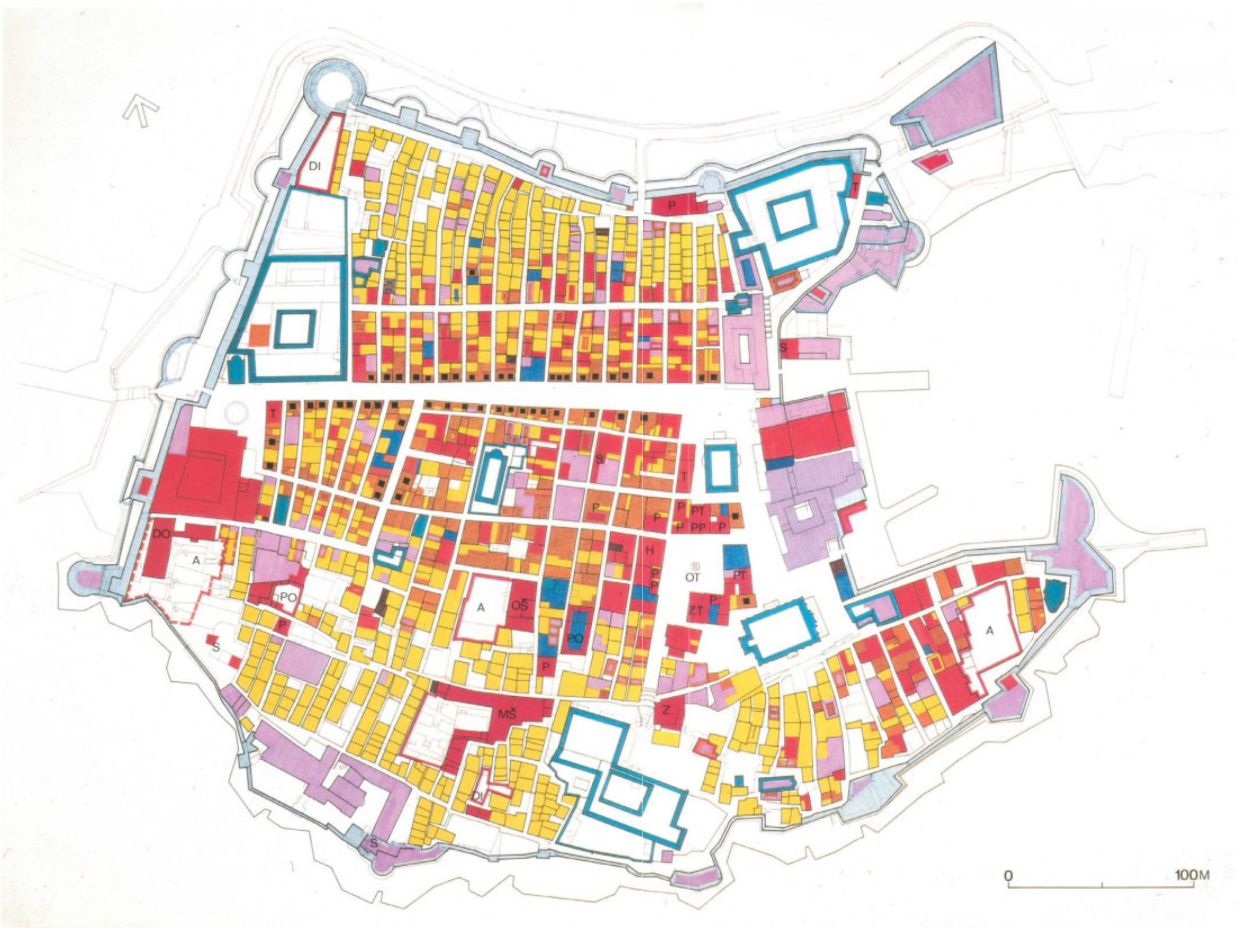


Figure 4. Urban plan of the Old City of Dubrovnik from 1982 (legend by color: yellow = residential buildings; pink = cultural; blue = management, administration, and economy; red and brown = tourism and stores) [47,48].

In general, the building stock has deteriorated due to inappropriate maintenance and the inability of the elderly population (private ownership) to bear the costs of renovation, which is also contributed by the demanding works and procedures for obtaining approval for construction projects. In addition, damage caused during the earthquake and inappropriate internal modifications of buildings also contribute to it. The Old City is treated as the cultural center and attractive tourist destination, apart from its administrative and residential content.

3. Design, Construction, and Retrofitting of Rector's Palace

The Rector's Palace in the Old City of Dubrovnik (see Figures 5–8) is a building of outstanding world historical and cultural heritage significance and value. It is included in the UNESCO World Heritage List [49] immediately after the 1979 M_w = 7.1 Montenegro earthquake caused structural damage to the building. In history, it was used as the seat of government and residence of the Rector, the highest political function in the Republic of

Dubrovnik (1358–1808), while today it serves as a museum. It is located on the edge of the eastern part of the Old City next to the city ramparts and the port (see Figures 2–4).

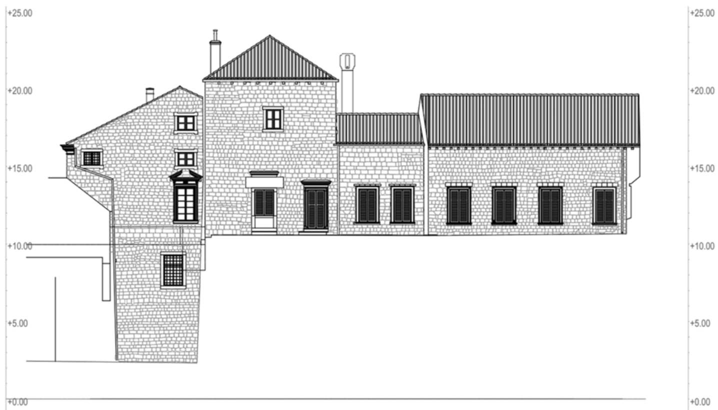
(**a**)

(**b**)

(**c**)

(**d**)

Figure 5. A view at the exterior and interior of the Rector's Palace architecture: (**a**) south-west corner of the building; (**b**,**c**) atrium; (**d**) arcades (courtesy of the Institute for the Restoration of Dubrovnik [14]).



(**a**)

Figure 6. *Cont.*

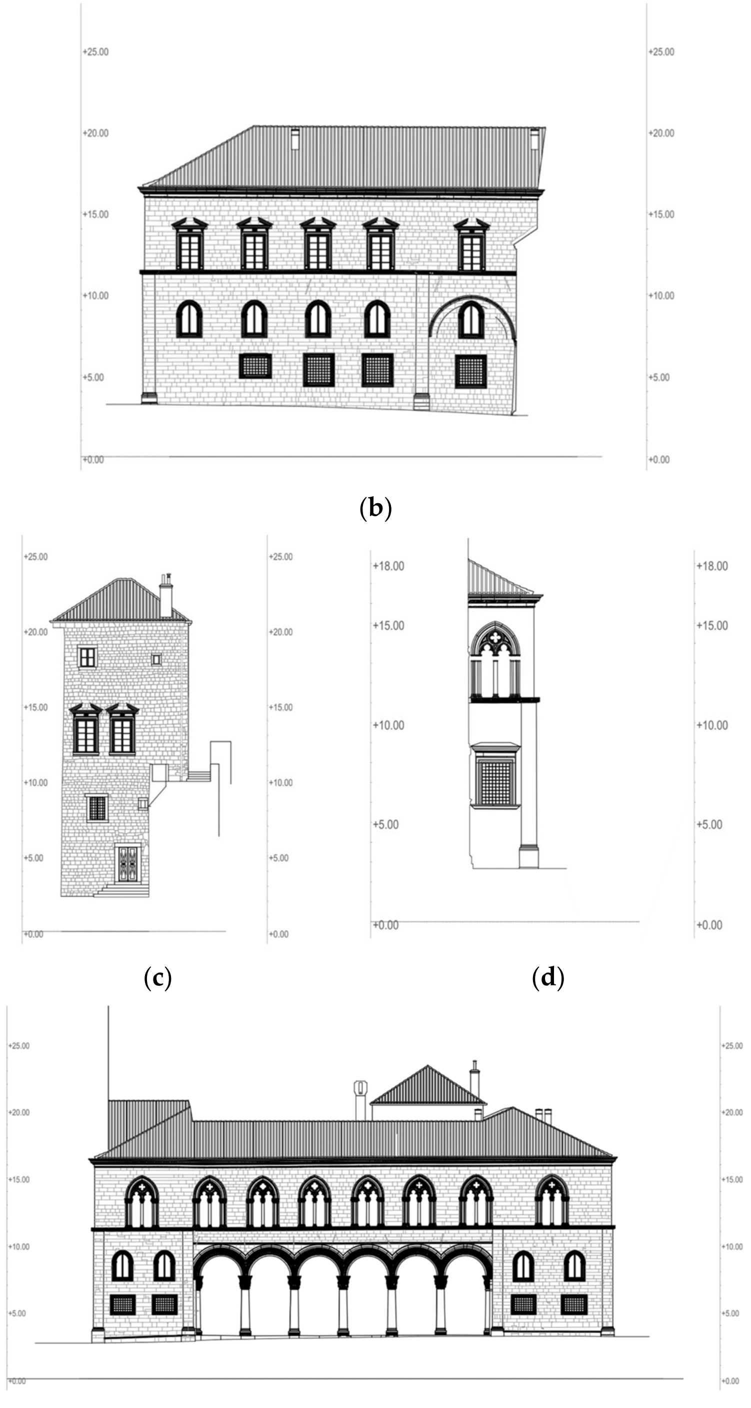


Figure 6. Facades of the Rector's Palace with historical architectural details: (**a**) east; (**b**) south first; (**c**) south second; (**d**) north and (**e**) west façade view (courtesy of the Institute for the Restoration of Dubrovnik).

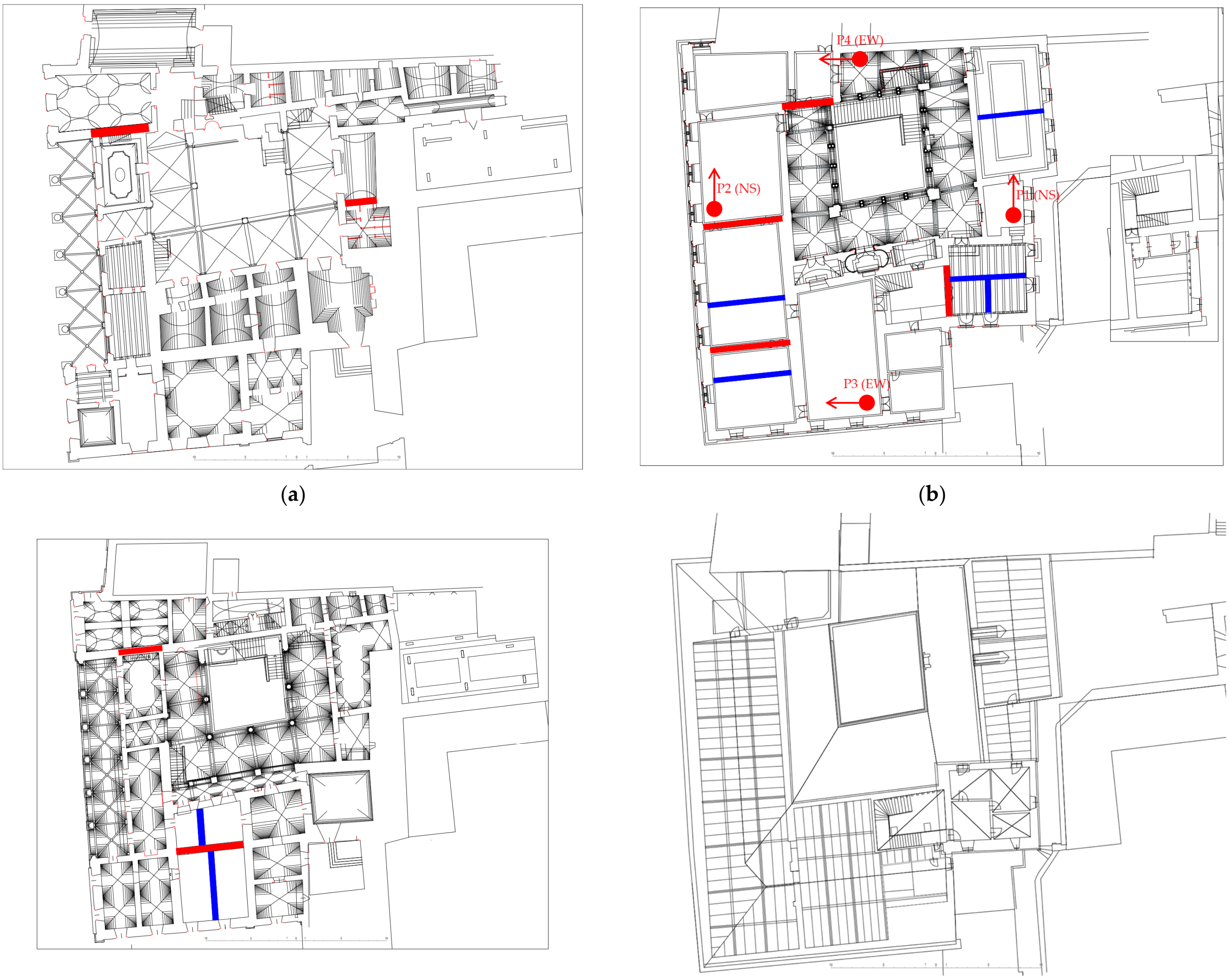
(**a**)

(**b**)

(**c**)

(**d**)

Figure 7. Selected cross-sections of the Rector's Palace: (**a**) "2-2"; (**b**) "3-3"; (**c**) "6-6"; (**d**) "9-9" as specified in original architectural drawings (courtesy of the Institute for the Restoration of Dubrovnik).



(a) (b) (c) (d)

Figure 8. Floor plans of the Rector's Palace after 1982–1984 retrofitting showing added/replaced (in red color) and removed (in blue color) stone masonry structural walls with reference to a pre-retrofitting design condition: (**a**) ground floor; (**b**) first floor including the position and the direction of the instruments used for ambient vibration measurements; (**c**) mezzanine; (**d**) attic (courtesy of the Institute for the Restoration of Dubrovnik).

The building was first mentioned as a *castrum* in 1272 and in 1296 as a *castellum*, and its original design was in accordance with its military purpose [47,48]. In 1349, it was mentioned as *palatium* and *palazzo maggior*. After the fire in 1435, it was severely damaged and then restored until 1443, according to the designs of Italian architect Onofrio di Giordano della Cava. In 1463, due to a gunpowder explosion, part of the building collapsed and caught fire, and the building was then restored to its present appearance by Italian architect Salvi di Michele.

The soil beneath the building consists of condensed sand and clay of medium and high plasticity with a thickness of 13–27 m (up to the bedrock). The groundwater (freshwater) level is about 1.5 m beneath the surface and about 0.75 m above the sea level. The building is founded on a strip masonry foundation of roughly dressed stone. The vertical structural system consists of three-layered stone masonry walls with a thickness of 0.45–1 m. The outer layers are from finely dressed stone and lime mortar, while the central fil is made from a large number of stone chippings and fill material with the addition of lime mortar. In compliance with the building code valid in the period of retrofitting 1982–1984 [22] and with the contemporary building codes [25], the building is highly irregular in plane and elevation. The floor structures of a pre-retrofitted building consisted of wooden joists and stone vaults.

The mound of material above the vaults reaches even 0.5 m, while in several places, the vaults are illogically formed due to the modifications from past interventions. The vault thickness is about 0.25 m.

The earthquakes of 1520 and 1639 of severe intensity I_{MCS} = VIII damaged parts of the building, while the earthquake of 1667, estimated at a violent and extreme intensity of I_{MCS} = IX–X [11,12,50], caused very heavy structural damage to the building but not its collapse [13]. The first documented post-earthquake retrofitting, during which, in addition to repairs, multiple steel ties were installed, was completed in 1704, when the baroque atrium was built at the same time (see Figure 5b,c). In 1843, steel ties were introduced on the western facade, but several rough construction interventions also damaged the structural form of the palace. In 1952, additional interventions were carried out at the palace, which were aimed at improving its state. Prompted by warnings resulting from the M_w = 6.2 1962 Makarska earthquake (severe to violent intensity I_{MCS} = VIII–IX) [51–53], in the period from 1968 to 1974, detailed investigative work was carried out at the palace on the initiative of the Institute for the Protection of Cultural Monuments in Dubrovnik. In the 1979 Montenegro earthquake, the Rector's Palace was significantly damaged. Structural walls were separated from the floor structures and partition walls with cracks in the vaults, including tilting of the facades. The retrofitting began in 1982 and ended in 1984. It is described in detail in [13], and the basic information about the locations and approach of retrofitting is given here.

The retrofitting of 1982–1984, performed in compliance with building code [22] demands, ensured the interconnectivity of structural components (as possible within the available budget). Before the retrofitting, cracks were observed throughout the building. Masonry walls were erected in places where they were previously removed (see Figure 8), i.e., in 1843, while several partition walls were removed. Steel anchors ensured the connectivity between the existing and newly built walls. The walls were connected horizontally in three levels by slabs and cross-beams, e.g., the foundation, first floor, and mezzanine level. The masonry strip foundations were strengthened by adding RC beams next to them and by connecting them with steel anchors. The earthquake dilatations were added in contact with the neighboring buildings (see Figure 7). By the post-retrofitting design performed (equivalent static load method), and by taking into account the unknowns, it was concluded that the building would not be structurally damaged in case of an I_{MCS} = VIII intensity earthquake; however, the building code demanding resistance [22] to an earthquake of an I_{MCS} = IX intensity was not fulfilled. The building could be structurally damaged but will not collapse (as supported by the post-earthquake damage surveys after past strong and moderate earthquakes).

4. Construction Materials

The construction material of the built heritage in the Old City of Dubrovnik (and the eastern Adriatic coast) consists primarily of high-quality crafted limestone blocks sourced from nearby quarries. Other construction materials used are lime mortar, timber, and bricks. The built heritage of stone masonry generally does not conform with the design criteria and construction rules for earthquake-resistant buildings or building walls of EN 1998-1:2004 and EN 1996-1-1:2005 building codes [24,25], in particular, besides the period of construction, due to a lack of adequate floor structure and the floor–wall connection [54,55]. Although natural stone masonry units may fulfill the required criteria (compressive strength normal $f_b \geq f_{b,min}$ = 5 MPa, and parallel to bed joints $f_{bh} \geq f_{bh,min}$ = 2 MPa, respectively), the structural walls do not, due to the poor quality of lime mortar used (compressive strength $f_m < f_{m,min}$ = 5 MPa) and the construction methodology/approach varieties (irregularities).

An extensive experimental and theoretical research program on natural stone masonry buildings and building walls (and constituent materials) of the Balkan peninsula was performed by [54,55] and presented in Figures 9–11. Prior to this program, earlier research by [56,57] resulted in experimental data on stone masonry walls and seismic (horizontal) shear force capacity design methodology.

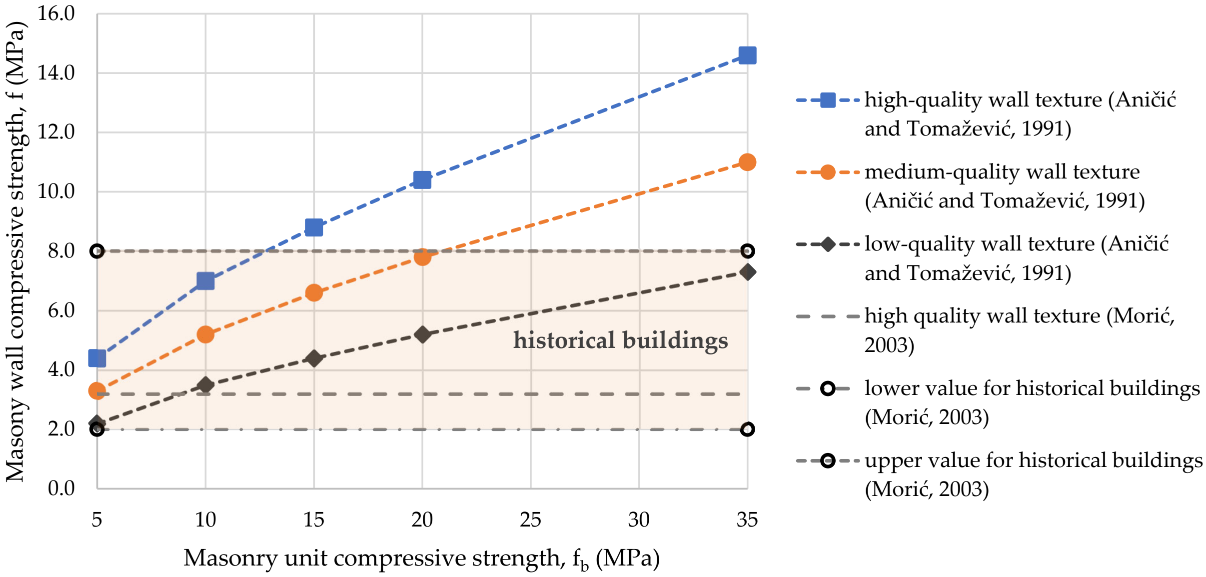


Figure 9. Compressive strength of natural stone masonry walls made with lime mortar, f (MPa), belonging to the eastern Adriatic coast with reference to the corresponding compressive strength of masonry units, f_b (MPa), in correlation with the quality of the wall texture (high, medium, and low) and reference values for historical buildings as given by [54,55,58,59].

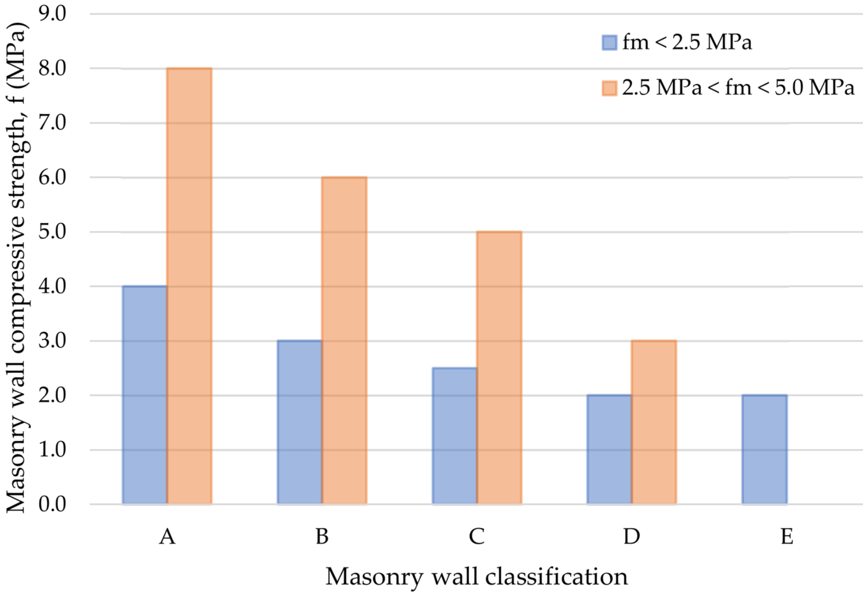


Figure 10. Compressive strength of natural stone masonry walls made with lime or cement–lime mortar, f (MPa), belonging to the eastern Adriatic coast with reference to wall classification (A–E) as proposed by [54,55] where letter symbols refer to (A) designated walls made of finely dressed and properly 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 number of stone chippings and fill material in the central layer, and with irregular joints; and (E) walls made of undressed stone with a large quantity of fill.

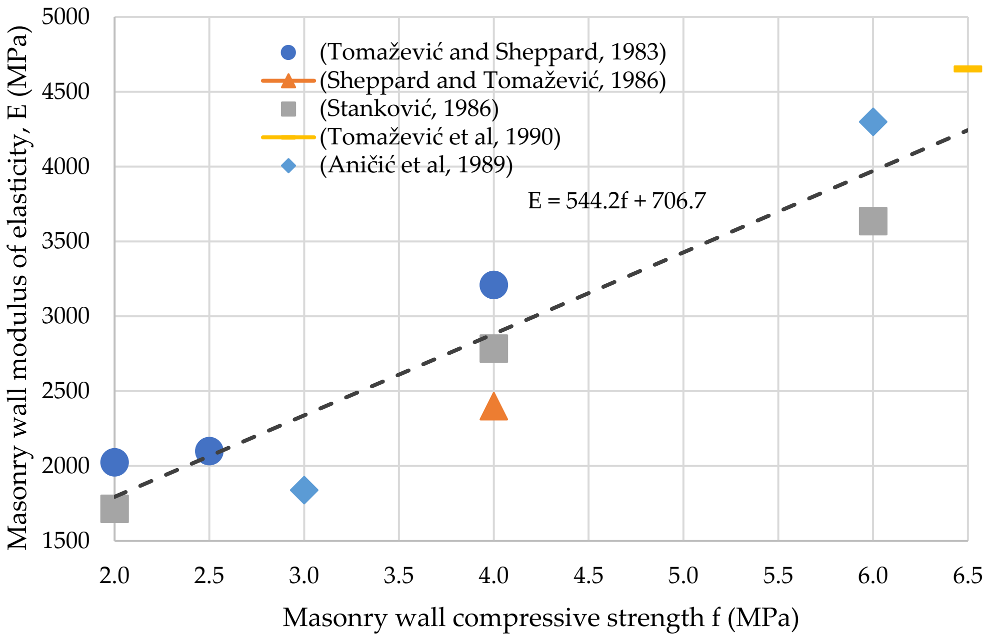


Figure 11. Modulus of elasticity of natural stone masonry walls made with lime mortar, E (MPa), belonging to the eastern Adriatic coast with reference to corresponding wall compressive strength, f (MPa), from test results, as given by [54,55,60–64].

Figure 9 shows the compressive strength of natural stone masonry walls made with lime mortar, f (MPa), belonging to the eastern Adriatic coast with reference to the corresponding compressive strength of masonry units, f_b (MPa), in correlation with the quality of the wall texture (high, medium, and low) and reference values for historical buildings as given by [54,55,58,59]. The walls are of high-quality texture, finely dressed stone masonry with an intermediate layer of fill. Based on the relations shown in Figure 9, the lower and upper limits of the compressive strength of stone masonry walls are 2.2 and 14.6 MPa [54,55]. The upper and lower values for historical buildings of 2.0 and 8.0 MPa, respectively, also stated in Figure 10, refer to (lime) mortar strength $f_m < 2.5$ MPa.

In addition, Figure 10 shows the compressive strength of natural stone masonry walls made with lime $f_m < 2.5$ (MPa) or cement–lime mortar, $2.5 < f_m < 5.0$ (MPa), belonging to the eastern Adriatic coast with reference to wall classification (A–E) as proposed by [54,55] 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 number of stone chippings and fill material in the central layer, and with irregular joints; and (E) walls made of undressed stone with a large quantity of fill. According to the EN 1996-1-1:2005 [24] building code, the wall compression strength estimate is based on the constituent contribution, i.e.,

$$f_k = K f_b^{0.7} f_m^{0.3} \tag{1}$$

where K is constant with a value of 0.45 for dimensioned natural stone; f_b is normalized compressive strength of a masonry unit; and f_m is the compressive strength of a mortar, ranging from 1.83 MPa (for f_b = 5 MPa and f_m = 2.5 MPa) to 8.8 MPa (for f_b = 35 MPa and f_m = 5.0 MPa), which corresponds to limits shown in Figure 9 as defined in [54,55].

The references [13,58,59,63,65,66] are particularly related to the characteristics of the Rector's Palace construction. The earthquake design requires the appropriate modulus of elasticity E, which can also be expressed in terms of compressive strength f of masonry walls

(B class in the case of Rector's Palace). The modulus of elasticity, besides the structure's mass, is critical in the calculation of the natural frequency of the building and, therefore, the earthquake performance. The adequate modulus elasticity was determined by structural model calibration with reference to measured natural frequencies. The initial, i.e., orientation values of the modulus of elasticity of natural stone masonry walls made with lime mortar, E (MPa), belonging to the eastern Adriatic coast with reference to corresponding wall compressive strength, f (MPa), from test results, as given by [54,55,60–64], are shown in Figure 11 and Table 1. As proposed by [54,55], and based on Figure 11 and Table 1 information, the lower limit (referring to walls of low-quality texture) of the modulus of elasticity can be expressed as E = 650 × f (MPa), while the upper limit (referring to walls of high-quality texture) as E = 900 × f (MPa), which is lower than the prediction E = 1000 × f (MPa) given in the EN 1996-1-1:2005 [24] building code. The corresponding value of stone masonry wall shear modulus G ranges from E/6 to E/4. In addition, the recommended values of stone masonry wall tensile strength f_t range from 0.09 to 0.3 MPa in relation to corresponding compressive strength ranging from 2.0 to 8.0 MPa, respectively.

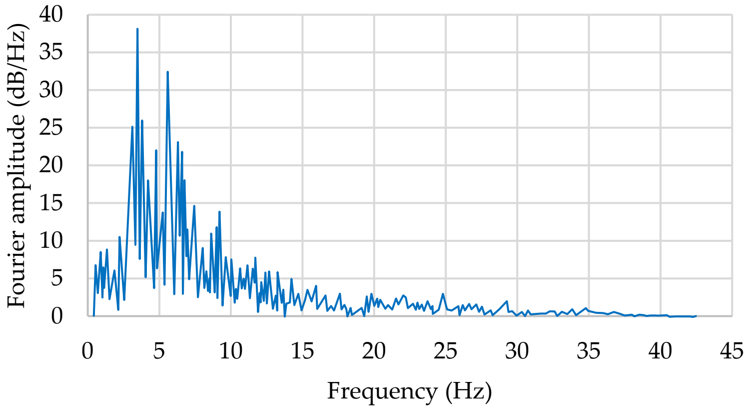
Table 1. Mechanical properties of natural stone masonry walls belonging to the eastern Adriatic coast obtained by experiments from different researchers [54,55].

Experimental Research Reference	Comp. Strength, f (MPa)			Elastic. Modulus, E (MPa)			Shear Modulus, G (MPa)		
Tomažević & Sheppard (1983) [60]	2.0	2.5		2025	2100		650	850	870
Tomažević & Sheppard (1986) [62]		4.0			2400			400	
Stanković (1986) [61]	2.0	4.0	6.0	1715	2785	3636	384	627	1245
Tomažević (1990) [64]		6.5			4652			488	
Tomažević (1992) [59]		3.0			1956			304	
Aničić (1989) [58,59]	3.0	6.0		1840	4300		350	950	

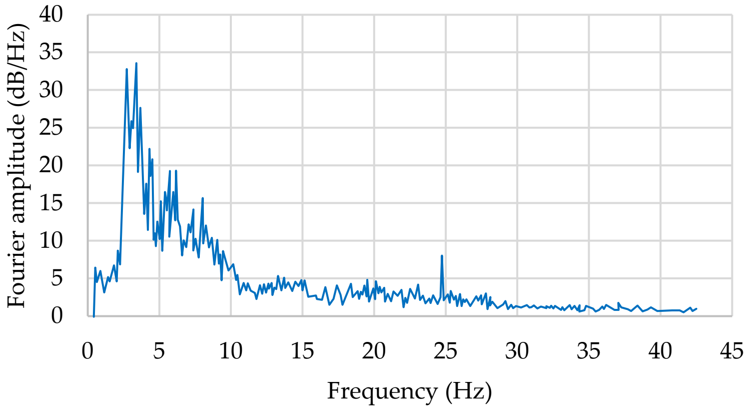
5. Building's Vibrational Characteristics

The vibrational characteristics of the Rector's Palace were determined via ambient vibration measurement performed by the Institute of Earthquake Engineering and Engineering Seismology (abbr. IZIIS) of the Saints Cyril and Methodius University in Skopje, FYR Macedonia, Yugoslavia (today's North Macedonia) in 1981, prior to the building's retrofitting, as described in [67] (see Figure 12).

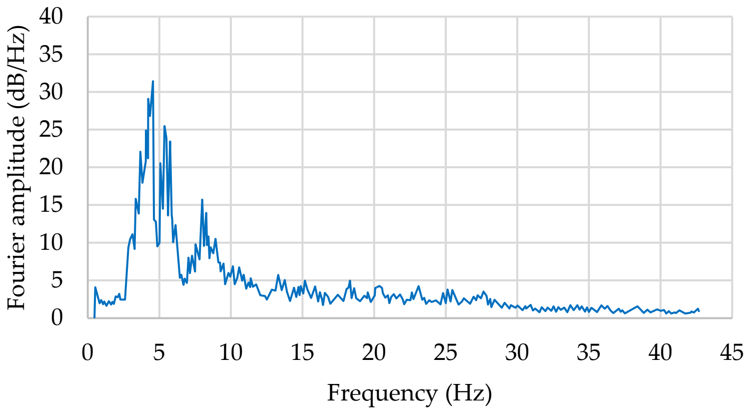
The measurement was undertaken in order to support the earthquake performance explanation of the building, as well as retrofitting strategies, by providing data for accurate prediction of earthquake-caused stress distribution in a structural model. At the time of measurement, the building had noticeable cracks in walls and ceilings visible from inside the building due to damage caused by the 1979 M_w = 7.1 Montenegro earthquake. The measurement was conducted using the "Ranger" model SS-1 seismometers (Kinemetrics, Pasadena, CA, USA). The measurement positions and directions are shown in Figure 8b. The results were presented in the form of Fourier spectra with noticeable natural frequencies of the building. The frequencies of potentially external (transient) excitations (not belonging to the structure itself) were removed by averaging the Fourier spectra, which distinguished the permanent frequencies. For illustration purposes, Figure 12a–c shows the averaged Fourier spectra for N-S and E-W directions and torsion appearance. From Figure 12a–c, the frequency of 2.80 Hz is clearly noticeable in the N-S direction, 2.67 Hz in the E-W direction, and 4.13 in torsion. Besides the distinguished peaks of the spectra, a multitude of peaks represent the natural frequencies of the individual structural components of the building. The dominant resonant frequencies f_n in Hz (and periods T_n in s) obtained using ambient vibration measurement are given in Table 2.



(**a**)



(**b**)



(**c**)

Figure 12. Example of Fourier amplitude spectra obtained via ambient vibration measurement in Rector's Palace for (**a**) N-S direction, (**b**) E-W direction, and (**c**) torsion, as given in [67].

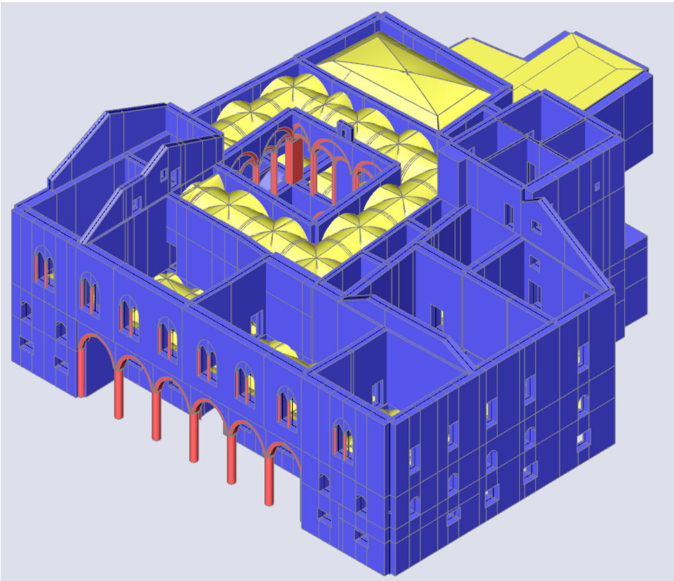
Table 2. Dominant resonant frequencies f_n in Hz (and periods T_n in s) obtained using ambient vibration measurement in Rector's Palace prior to retrofitting [67].

Direction	Dominant Resonant Frequencies f_n in Hz (and Periods T_n in s)							
	f_1 (T_1)	f_2 (T_2)	f_3 (T_3)	f_4 (T_4)	f_5 (T_5)	f_6 (T_6)	f_7 (T_7)	f_8 (T_8)
N-S	2.80 (0.36)	3.33 (0.30)	-	5.20 (0.19)	6.08 (0.17)	7.74 (0.13)	11.07 (0.09)	23.36 (0.04)
E-W	2.67 (0.38)	3.20 (0.32)	4.00 (0.25)	-	5.87 (0.17)	7.47 (0.13)	-	23.20 (0.04)
Torsion	-	-	4.13 (0.24)	5.07 (0.20)	-	7.60 (0.13)	12.51 (0.08)	23.68 (0.04)

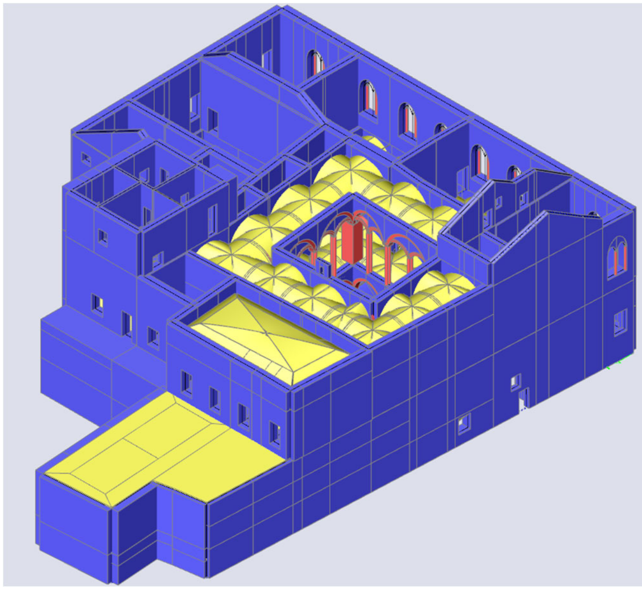
By inspection of the averaged Fourier spectra (Figure 12a–c), it was observed that the dominant resonant frequencies of the building are within the range of 3.0 to 5.0 Hz, which corresponds well to the expected values of the dominant (period) frequency range of earthquake action, i.e., 0–5 Hz [68], and poses a risk to a building. More specifically (see Table 2), in terms of natural periods, the dominant period of the earthquake action of 0.3–0.4 s could cause very heavy damage or destruction of the building. This also corresponds to Type 1 and Type 2 elastic response spectra peak values used to represent the seismic action by EN1998-1:2004 [25]. The wooden joists used for floor structures (2nd floor in a post-retrofitted building) were indirectly represented in the model by weight, i.e., as the loading on the supporting walls, including the corresponding permanent and variable loads acting on the floor [69]. The concrete class C25/30, namely elasticity modulus, E_{cm} = 31 GPa [30], was adopted for the RC slabs in the mezzanine and the first floor in the post-retrofitted building. The direct modeling of the wooden joists, e.g., wooden beams with their exact geometry semi-hinged to supporting walls, was avoided because their contribution to the overall earthquake resistance of the building is ideally 10 to 30% compared to the building with "absolutely rigid floor structures" [54,55]. The building considered is in fact a historical building with diminished structural capacity caused by its use, aging, and several major earthquakes and other disastrous events throughout its history. Therefore, with their omission in the model the most unfavorable building's structural response overall and, in particular, of structural walls was obtained.

6. Structural Assessment and Performance

The overall earthquake performance of the Rector's Palace in the Old City of Dubrovnik, Croatia, a cultural heritage building that was retrofitted in 1982–1984 and later (see Section 3), was assessed by a preliminary spatial finite element linear–elastic macro-modelling approach and the response spectrum analysis, in computer program SCIA ENGINEER [70] (see Figure 13). Performance was assessed with reference to contemporary building code requirements [24,25,30,71,72] via a calibrated spatial structural finite element model to determine its structural weaknesses and protection level against strong earthquakes. Considered were the return period of 95 (probability of exceedance 10% in 10 years), 225 (probability of exceedance 20% in 50 years), and 475 years (probability of exceedance 10% in 50 years) in compliance with the Earthquake Hazard Maps of Republic of Croatia [15,73], which correspond to limit states of damage limitation (DL), significant damage (SD), and near collapse (NC), respectively [72]. The overall assessment preliminary structural model is used as an indicator for strengthening the intervention aimed at improving the earthquake behavior of the building as a whole, as well as by individual components. The soil–structure interaction effects were not considered in the analysis, i.e., the rigid base (foundation) connection to ground type A [25] $v_{s,30}$ > 800 m/s, namely rock or other rock-like geological formation, including at most 5 m of weaker material at the surface of the region, was assumed, which provides the most unfavorable outcomes with regard to design criteria. Adopted is the finite element mesh size of 0.5 m after performing the mesh sensitivity study with 0.25, 0.5, and 1.0 m mesh sizes. The calibration of the model was performed based on the pre-retrofitted building's condition (before retrofitting of the 1982–1984 period) against the value of the average value of the N-S and E-W value of the fundamental period, i.e., T_1 = 0.37 s (see Table 2).



(a)



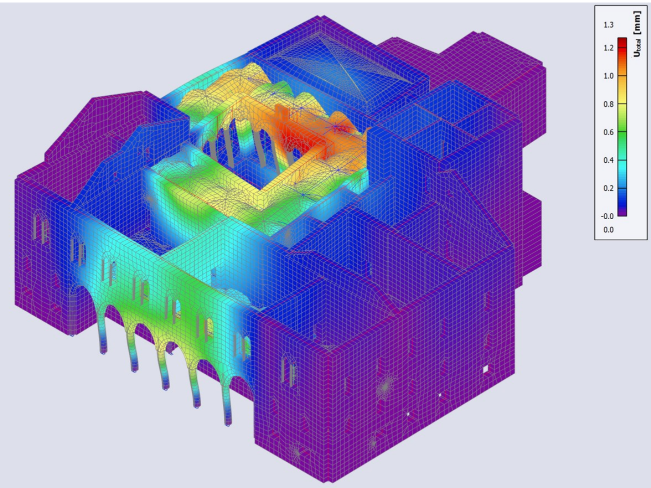
(b)

Figure 13. Finite element model of Rector's Palace built in a computer program SCIA ENGINEER [70]: (**a**) southwestern view and (**b**) northeastern view of the building.

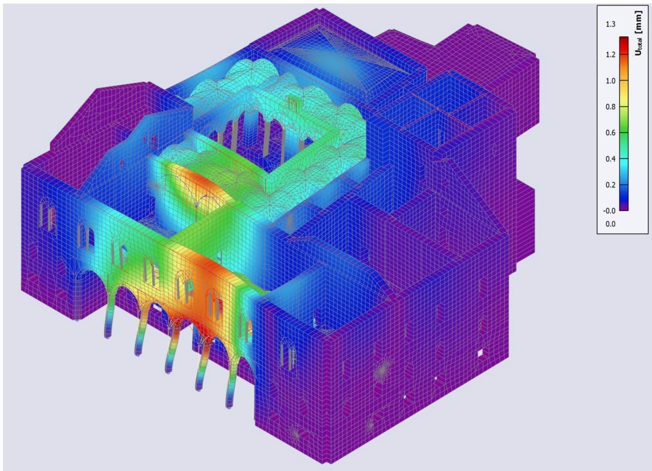
The finite element mesh sensitivity study resulted in the following building's fundamental period T (s) values (with the corresponding finite element size): T_1 = 0.375 s (size of 1.0 m), T_1 = 0.37 s (size of 0.5 m), and T_1 = 0.3698 s (size of 0.25 m). The model comprised (with adopted meshing) 47,980 2D (3-node triangular and 4-node quadrilateral isoparametric shell elements) and 2068 1D (2-node beam finite elements) with 45,945 mesh nodes in total.

With regard to the pre- and post-retrofitting structural model, the main differences were in the addition and removal of structural stone masonry walls, as shown in Figure 8, and in enabling the rigid wall–slab connection (and diaphragm) assumed for walls that were connected horizontally in three levels by reinforced concrete slabs and cross-beams, e.g., on the first floor, and in mezzanine level (in place of wooden joists in a pre-retrofitting design condition, which were not considered directly in the model in the pre-retrofitting design condition). The latter was not implemented over the vaults (see Figure 13).

The calibration was performed using the elasticity modulus of masonry walls of class B (see Section 4), which was found to have an overall mean value of about E = 1900 MPa for the whole building. After calibration, the model was upgraded in order to take the retrofitting of 1982–1984 and later into account (see Section 3). It was found that there is a slight decrease in the first average (N-S and E-W direction) fundamental period from T_1 = 0.37 s (f_1 = 2.72 Hz) to T_1 = 0.34 s (f_1 = 2.96 Hz), as shown in Figure 14. The connection of the structural interventions with the rest of the building is adopted among other parts of the structure without the introduction of special approaches to modeling, i.e., as a perfect connection.



(**a**)



(**b**)

Figure 14. The fundamental period of Rector's Palace for a: (**a**) pre-retrofitted condition T_1 = 0.37 s, f_1 = 2.72 Hz, $W_{EW,1}/W_{EW,tot}$ = 3.6%, and $W_{NS,1}/W_{NS,tot}$ = 10.0%; (**b**) post-retrofitted condition T_1 = 0.34 s, f_1 = 2.96 Hz, $W_{EW,1}/W_{EW,tot}$ = 0.58%, and $W_{NS,1}/W_{NS,tot}$ = 18.0%.

The following quantities were considered as loads to the building: permanent action (G): self-weight of the mound above vaults = 14 kN/m^3; self-weight wooden joists = 8 kN/m^3; self-weight roof (structure and tiles) = 5.8 kN/m3; self-weight of masonry construction = 25 kN/m^3; variable action (Q): museum (C3 category) = 5 kN/m^3; roof = 0.75 kN/m^3; seismic action (A): type 1 response spectrum; soil type A (see Table 3); damping ratio 0.05. The importance factor for the building selected is γ_I = 1.4. The seismic combinations used are stated in Table 4. The results of structural analysis are given in Figures 15–18 in the form of mode shapes (twelve considered), spatial displacements and principal compressive and tensile stresses indicating the path and pattern of potential structural damage and its prevailing direction. The analysis is aimed at determining the critical building parts and revealing the structural weaknesses with reference to expected earthquake action. The building is considered un-damaged for analysis purposes.

Table 3. The seismic action definition parameters are in compliance with [15,25].

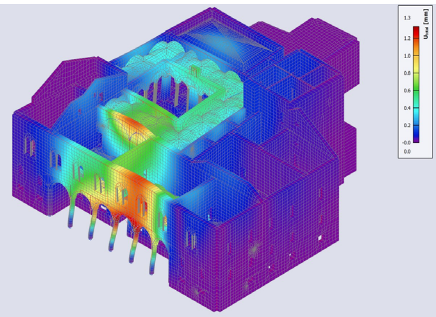
Ref. Return Period (Years)	Importance Factor γ_I	Reference PGA a_{gR} (g)	DGA a_g (m/s^2)
95		0.16	2.20
225	1.4	0.22	3.02
475		0.30	4.12

Table 4. The seismic combinations applied to the structural model of the Rector's Palace are in compliance with [71,72].

Load Combination 1—LC1	Load Combination 2—LC2
$\sum G + E_{Ed,x} + 0.30E_{Ed,y} + \sum \Psi_2 Q$	$\sum G + 0.30E_{Ed,x} + E_{Ed,y} + \sum \Psi_2 Q$

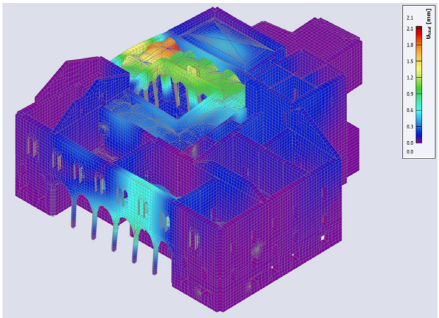
Ψ_2 = 0.3 for variable action of the building category C1.

Mode 1



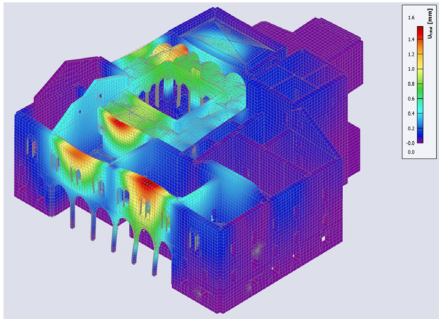
$T_1 = 0.34$ s; $f_1 = 2.96$ Hz;
$W_{EW,1}/W_{EW,tot} = 0.58\%$;
$W_{NS,1}/W_{NS,tot} = 18.0\%$

Mode 2



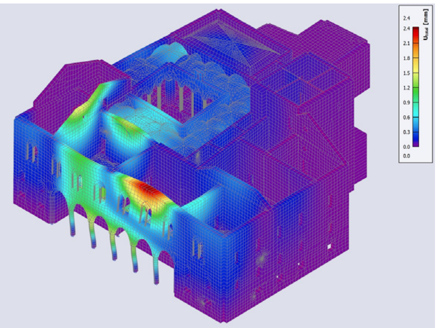
$T_2 = 0.30$ s, $f_2 = 3.31$ Hz;
$W_{EW,2}/W_{EW,tot} = 5.74\%$;
$W_{NS,2}/W_{NS,tot} = 0.16\%$

Mode 3



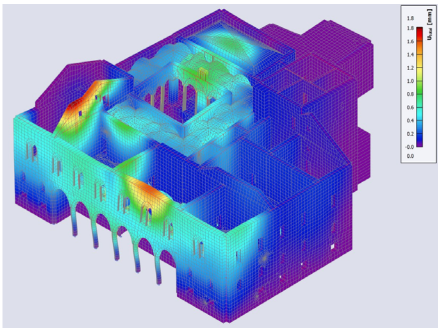
$T_3 = 0.28$ s, $f_3 = 3.58$ Hz;
$W_{EW,3}/W_{EW,tot} = 2.90\%$;
$W_{NS,3}/W_{NS,tot} = 2.60\%$

Mode 4



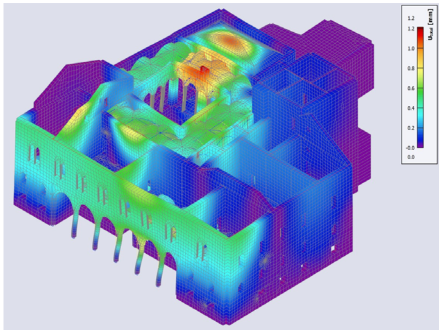
$T_4 = 0.27$ s, $f_4 = 3.77$ Hz;
$W_{EW,4}/W_{EW,tot} = 0.19\%$;
$W_{NS,4}/W_{NS,tot} = 0.0\%$

Mode 5



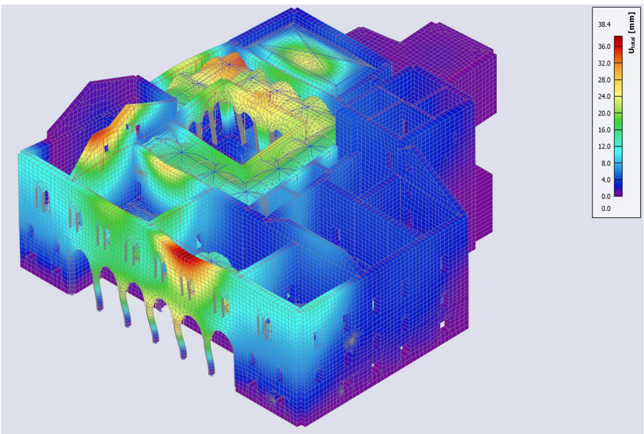
$T_5 = 0.26$ s, $f_5 = 3.79$ Hz;
$W_{EW,5}/W_{EW,tot} = 1.51\%$;
$W_{NS,5}/W_{NS,tot} = 0.58\%$

Mode 6

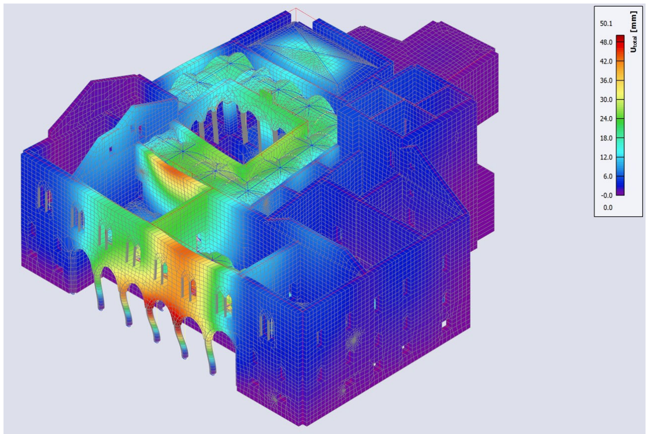


$T_6 = 0.26$ s, $f_6 = 3.88$ Hz;
$W_{EW,6}/W_{EW,tot} = 19.3\%$;
$W_{NS,6}/W_{NS,tot} = 0.52\%$

Figure 15. The first six mode shapes (out of twelve considered) of the post-retrofitted Rector's Palace based on the structural finite element model analysis.



(**a**)



(**b**)

Figure 16. Spatial displacement distribution in mm on Rector's Palace for the reference return period of T_{NCR} = 475 years: (**a**) load combination—LC1; (**b**) load combination—LC2.

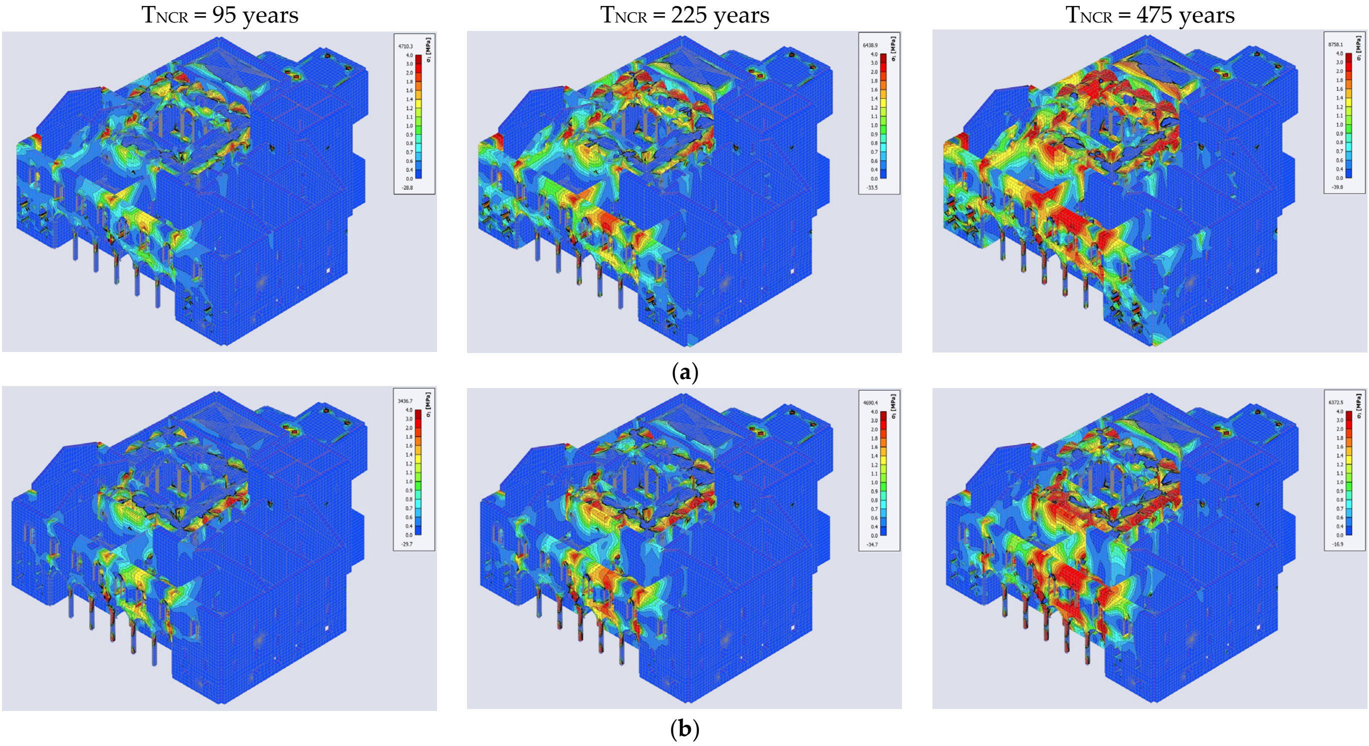


Figure 17. Principal tensile stresses, σ_1 (MPa), on the Rector's Palace, at reference return periods, T_{NCR}, of 95, 225, and 475 years: (**a**) load combination—LC1; (**b**) load combination—LC2.

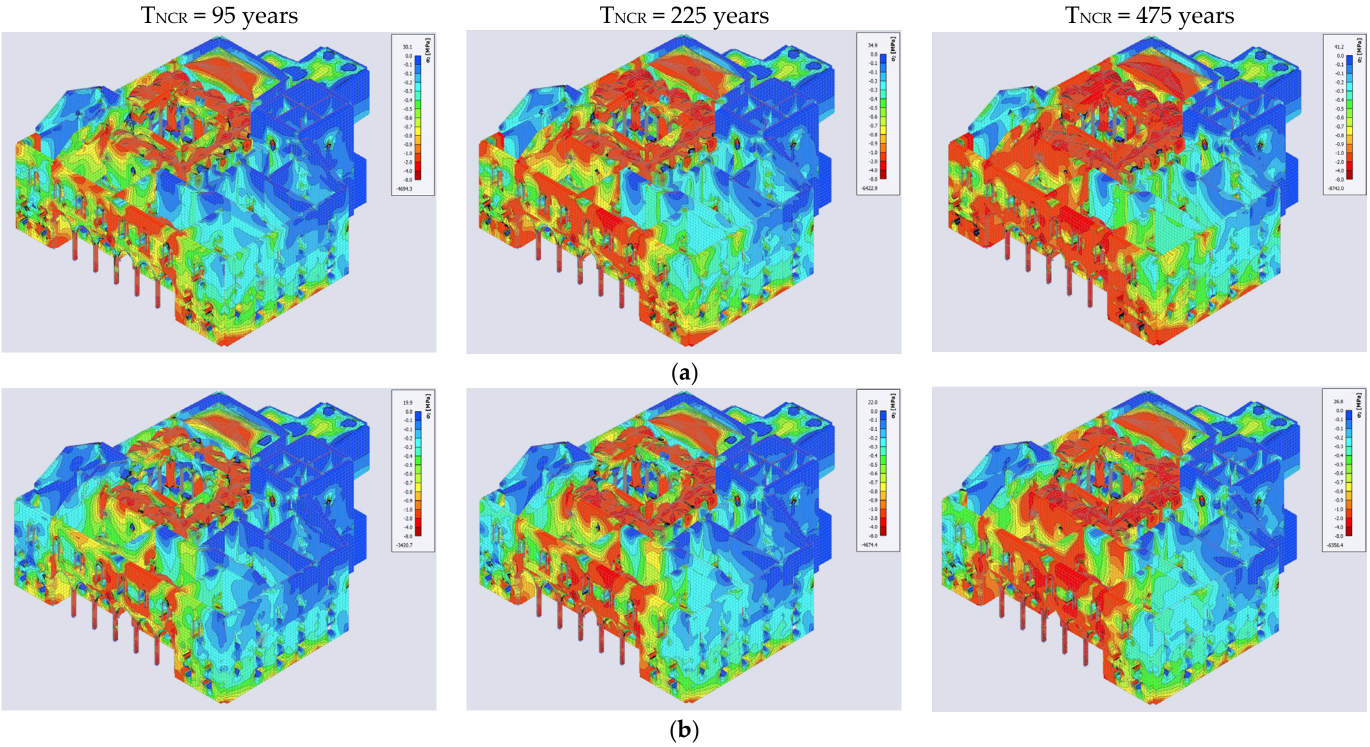


Figure 18. Principal compressive stresses, σ_2 (MPa), on the Rector's Palace, at reference return periods, T_{NCR}, of 95, 225, and 475 years: (**a**) load combination—LC1; (**b**) load combination—LC2.

The initial value of behavior factor q = 1.5 is adopted based on the building code [24,25] criteria and recommendations for unreinforced masonry construction in low seismicity cases that correspond to a pre-code, i.e., historical building construction practice. A seemingly conservative approach was adopted by assuming the same value of behavior factor for pre- and post-retrofitting design conditions mainly for comparison reasons.

The influence of various design factors, such as construction material, structural form, and excitation, on earthquake performance and vulnerability of the building, which are mutually dependent, are discussed in the following section.

7. Discussion

The overall earthquake performance of the Rector's Palace in the Old City of Dubrovnik, Croatia, a cultural heritage building, was assessed with reference to contemporary building code requirements [25,72] via a calibrated spatial structural finite element model in order to determine its structural weaknesses and protection level against strong earthquakes. Considered were the return period of 95 (probability of exceedance 10% in 10 years), 225 (probability of exceedance 20% in 50 years), and 475 years (probability of exceedance 10% in 50 years) in compliance with the Earthquake Hazard Maps of Republic of Croatia [15,73] (see Figure 19), which correspond to limit states of damage limitation (DL), significant damage (SD), and near collapse (NC), respectively [72].

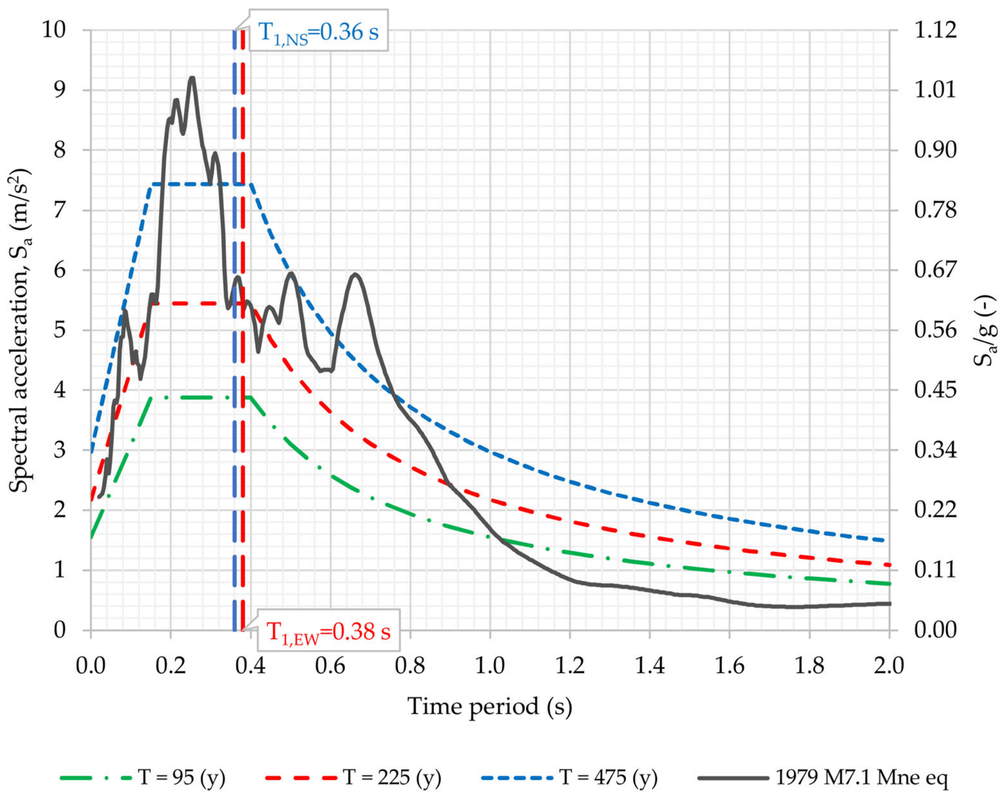


Figure 19. Response spectrum of Type 1 for reference return periods, T_{NCR}, of 95, 225, and 475 years [25], respectively, and of the M_w = 7.1 1979 Montenegro earthquake [74,75] recorded at Herzeg Novi station in the N-S direction for behavior factor q = 1.0 (at a 50 km distance from Dubrovnik's Old City) with the corresponding building's measured pre-retrofitting fundamental periods in the N-S and E-W directions, i.e., $T_{1,NS}$ and $T_{1,EW}$, respectively.

In comparison with the corresponding building code response spectrums, Figure 19 shows the response spectrum of the 1979 M_w = 7.1 Montenegro earthquake [74,75] recorded at Herzeg Novi station in the N-S direction (at a 50 km distance from Dubrovnik's Old City) for behavior factor q = 1.0, the building's fundamental periods in the N-S and E-W directions, i.e., $T_{1,NS}$ and $T_{1,EW}$, respectively. The geology and soil conditions of the Montenegrin and Croatian coasts in the observed area have matching characteristics. As seen in Figure 19, the measured fundamental frequencies (periods) of the building in the

NS and EW direction, namely, $T_{1,NS}$ = 0.36 s and $T_{1,EW}$ = 0.38 s, comply with the highest demand represented by the building code and the 1979 M_w = 7.1 Montenegro earthquake response spectrum.

Consequently, the earthquake-related risk to the whole built heritage of Dubrovnik's Old City is relatively high, as evident from seismic microzoning earthquake intensity ma (in compliance with the Mercalli–Cancani–Sieberg (MCS) scale) shown in Figure 20 and damage map in Figure 2.

Figure 20. Seismic microzoning earthquake intensity map of the Old City of Dubrovnik in compliance with the Mercalli−Cancani–Sieberg (MCS) scale (publicly available at URL: https://zod.hr/obnova-dubrovnika/potres-1979-i-aseizemicka-sanacija/; accessed on 22 September 2023).

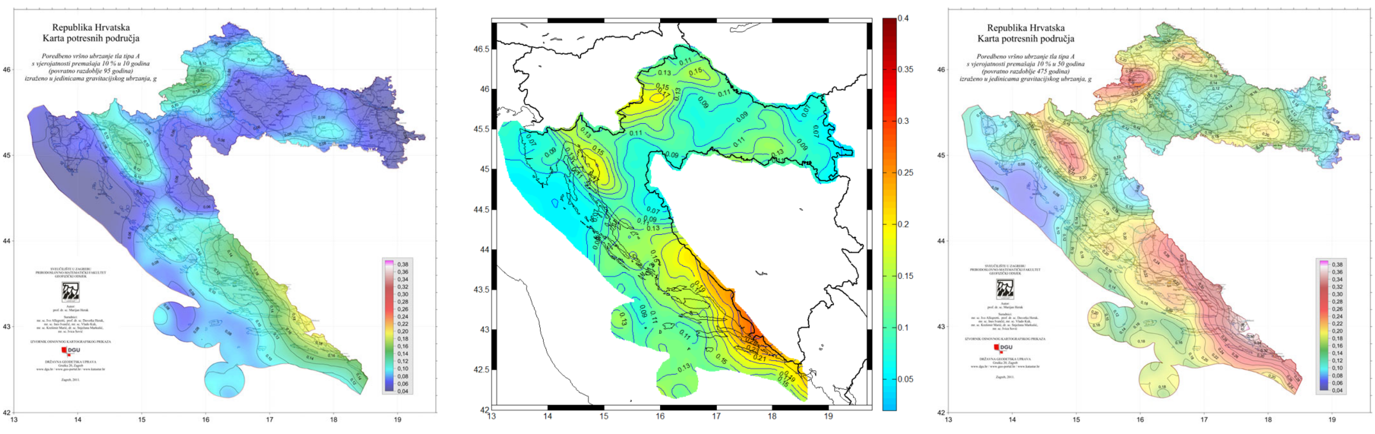
The overall assessment preliminary structural model is used as an indicator for strengthening the intervention aimed at improving the earthquake behavior of the building as a whole, as well as by individual components. The building belongs to vulnerability class B in pre- and C in post-retrofitting design conditions in compliance with EMS-98 [27] and its structural characteristics and contemporary building code requirements [24,25,30]. The masonry construction of Rector's Palace (in the floor plans (see Figures 8–11)) is represented by layered walls whose thickness is approx. $40 \leq t_{ef} \leq 100$ cm (i.e., $t_{ef,min}$ = 35 cm [25]), i.e., class B. One can wrongly assume that by increasing thickness, the resistance of a building's earthquake performance improves. This, however, in the case of stone masonry, depends on the cross-section, e.g., masonry wall classification A–E with reference to texture quality and compressive strength, as shown in Figure 10. More research is required before the effect of the thickness of different masonry wall classifications on a building's earthquake performance is completely described.

In considering the frequencies of vibration obtained from the field measurements, besides the building's (dominant) natural frequencies (see Table 2 and Figure 15), the ones from the individual structural components or structural parts could be observed (see Figure 12), which is an indicator of the poor structural inter-connectivity or damage. However, eight modes were observed by measurements, which was helpful for assessing the model by performing its calibration and validation. The total effective mass participation for the first six modes of vibration corresponds to approximately 30% in the EW and 25% in the NS building's direction, respectively. In order to reach higher mass participation, the calculation of a large number of modes, i.e., approximately 200 modes, is required to reach 90% of the total mass participation in both horizontal directions.

The performance of the structure was evaluated using the linear elastic approach (and by assuming its inelastic behavior in other terms such as behavior factor). While the linear approach is adequate for structural response analysis, it is unable to represent actual modes of failure compared to non-linear analysis (e.g., direct integration time–history analysis, etc.). Additionally, the limitation of the model was that as well as in the design practice, once calibrated against the fundamental period and validated against higher mode periods, it assumed the mean value of the elasticity modulus was equal for the whole structure. In order to subsequently confirm the accuracy of the structural model, it is advisable to carry out the ambient vibration measurements on the existing structure.

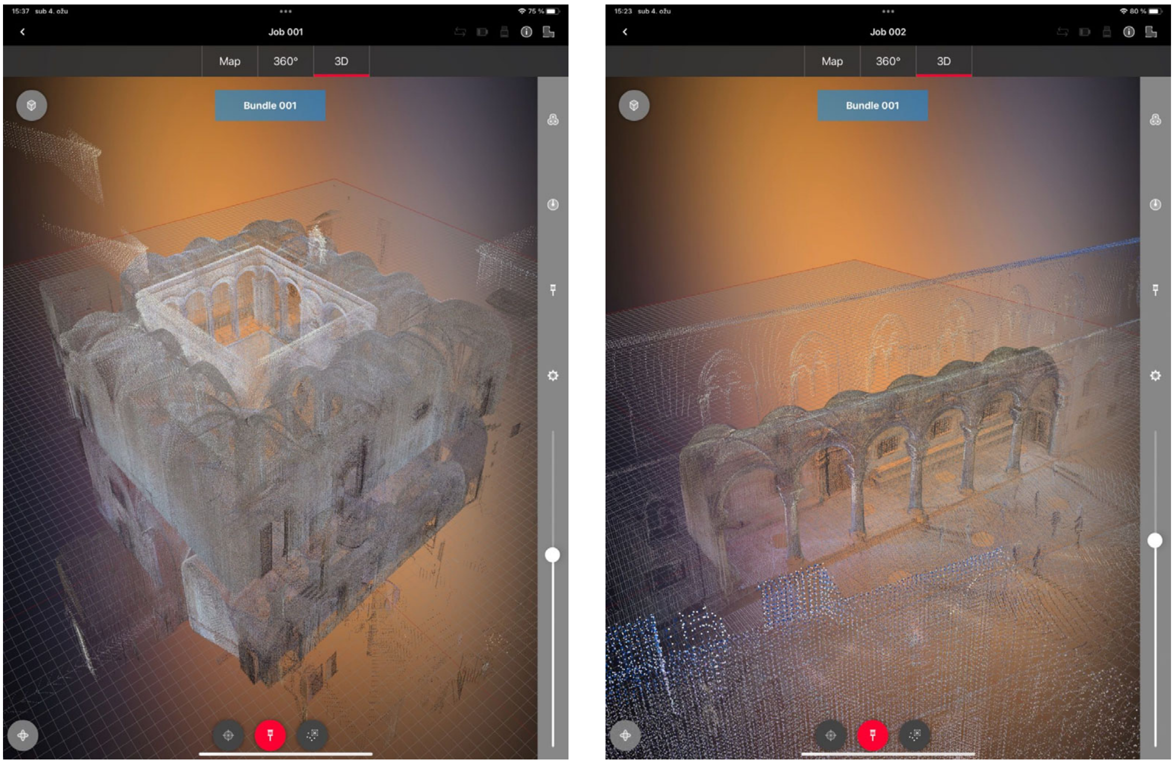
The earthquake performance and vulnerability were assessed quantitatively (via the displacement and stress levels) and qualitatively (via the volume affected by damage) using the spatial displacement and principal stress distribution. In Figure 16, the spatial displacement distribution indicates the near collapse (out-of-plane) limit state (d = 50 mm; d_r = 4% with reference to h_{tot}) at the top of the western façade (above arcades). The principal tensile stresses, σ_1 (MPa), shown in Figure 17a,b, indicate the values exceeding the tensile strength, f_t, ranging from 0.09 to 0.3 MPa [54,55] (see Section 3), at all limit states, i.e., damage limitation (DL), significant damage (SD), and particularly near collapse (NC). The principal compressive stresses, σ_2 (MPa), shown in Figure 18a,b, by referring to the highest expected compressive strength value for historical masonry construction of f = 8.0 MPa, indicate the damageability even at the damage limitation (DL) state, as they vary between the limit states by the volume affected by damage (50% of volume at a near-collapse (NC) state).

The damage evolution based on principal tensile stress, σ_1 (MPa), observation in Figure 17a,b at return periods T_{NCR} = 95 (a_g/g = 0.16), 225 (a_g/g = 0.21), and 475 (a_g/g = 0.30) years (see Figure 21), reveals that in spite of the interventions applied to atrium's vertical structural elements (namely, stone columns and masonry walls) the adjacent stone vaults still remain the most vulnerable building part to earthquakes, even for the damage limitation (DL) limit state design requirements, i.e., T_{NCR} = 95 (a_g/g = 0,16). Considering the corresponding increased return period principal tensile stress values, i.e., at T_{NCR} = 225 and 475 years, besides the building's atrium, the vulnerability of arcades (western façade) becomes evident and highly sensitive to out-of-plane failure (see also Figures 16b and 22b).



(**a**) (**b**) (**c**)

Figure 21. The Earthquake Hazard Maps of the Republic of Croatia for the return period of (**a**) 95, (**b**) 225, and (**c**) 475 years (publicly available at URL: http://seizkarta.gfz.hr/hazmap/karta.php; accessed on 22 September 2023).



(**a**) (**b**)

Figure 22. Images obtained using 3D laser scanning performed via the Leica BLK360 of Rector's Palace: (**a**) atrium and (**b**) arcade.

The distribution of principal compressive stresses, σ_2 (MPa) in Figure 18a,b confirms the regions of critical exposure to earthquakes (achieving the highest permissible values, i.e., f = 8 MPa) at observed limit states as seen in Figure 17a,b, namely, atrium at T_{NCR} = 95 (a_g/g = 0.16) and arcades at T_{NCR} = 225 (a_g/g = 0.21), also indicating the possibility of compressive crushing of stone columns and masonry walls.

The occurrence of structural damage, based on Figures 16–18, is expected at the atrium and arcades (western façade), which is recognized as a building's vulnerability in surveys from past strong earthquakes. The data shown in Figures 16–18 confirm the necessity of strengthening interventions (past and future) with the purpose of reducing the building's exposure to strong earthquakes, particularly when dealing with buildings of outstanding cultural heritage significance and value.

In order to ensure the preservation of the most vulnerable parts of the building and to collect information about the irregular geometry of the atrium and arcades, 3D laser scanning was performed with a Leica BLK terrestrial scanner (see Figure 22) [76].

The collection of data using a 3D laser scanning technique was required due to the complexity of the form of observed building parts and their art and architectural value and for the accuracy of the computational model geometry.

In computational modeling of historical urban architecture, consisting of poorly to well-built regular or irregular masonry construction, the assessment of earthquake performance using two, or (preferably) three-dimensional finite [77,78] or discrete [79,80] element micro- or macro-models (linear and non-linear), is the most efficient, comprehensive and revealing approach available. It has a major advantage in easily allowing changes in a building's structural and material characteristics and a straightforward relation with its measured vibrational characteristics for the purpose of model calibration.

8. Conclusions

The restoration of Dubrovnik's Old City has been performed continuously from 1979 after the M_w = 7.1 Montenegro earthquake up to today, with an interruption during the Homeland War period between 1991 and 1995. The Rector's Palace (1272–today) is a cultural heritage building of outstanding significance and value and was listed in 1979 as a UNESCO World Heritage Site. The building underwent several reconstructions and retrofitting during its life period triggered by various hazardous events such as explosions, fires, and earthquakes.

Based on the preliminary case study performed on the overall earthquake performance of the pre- and post-retrofitting design of Rector's Palace before 1982 and after 1984, respectively, the following conclusions were made:

- Historical seismicity (more than ten past earthquakes of $I_{MCS} \geq$ VIII intensity) and geology (sea embayment with shallow deposits of sand and clay) were considered in order to perform a credible analysis of the building's earthquake vulnerability with reference to contemporary building code demands (for return periods T = 95, 225, and 475 years);
- Building retrofitting performed in the past (the most significant in the period between 1982 and 1984) based on codified, inadequate, or non-codified approaches vary through arbitrary or partial measures to thorough earthquake design criteria implementation (with reference to the building code of the period) and reveal the potential of building damage in the account of the earthquakes expected in the region;
- Due to the difficulty and complexity of the task regarding restrictions imposed on observed UNESCO-listed heritage buildings to perform experiments in situ, the bibliography resources were used to assess the construction material and vibrational characteristics, with estimates of the range of their validity on the observed and similar unreinforced stone masonry buildings, most of them related to the period of the post-1979 Montenegro earthquake restoration period;
- The aforementioned material and structural characteristics were crucial in establishing the modeling strategy, e.g., finite element structural macro-modeling approach and response spectrum analysis, and employed in the development and calibration of the model;
- The earthquake damage evolution, at each of the prescribed design limit states, highlighted the heritage building's structural weaknesses, namely the atrium, and arcades, as the most vulnerable parts of the building;
- In order to preserve their art form and geometry, in case of damage and for future restoration purposes due to the high risk of earthquakes, the 3D laser scanning data collection was performed and assessed.

Based on the outstanding value and importance of the Rector's Palace, and by considering the consequences of its damage or collapse, the current lack of data on its overall earthquake performance, the case study conducted is a ground basis for creating measures against destructive earthquakes expected in the region, as evident by historical records.

It provides a basis for future more detailed finite or discrete (linear or non-linear) element damage and failure analyses of the building or its parts the most susceptible to a certain degree of damage or even collapse and their retrofitting possibilities.

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References

1. Markušić, S.; Stanko, D.; Korbar, T.; Belić, N.; Penava, D.; Kordić, B. The Zagreb (Croatia) M5.5 Earthquake on 22 March 2020. *Geosciences* **2020**, *10*, 252. [CrossRef]
2. Markušić, S.; Stanko, D.; Penava, D.; Ivančić, I.; Oršulić, O.B.; Korbar, T.; Sarhosis, V. Destructive M6.2 Petrinja Earthquake (Croatia) in 2020—Preliminary Multidisciplinary Research. *Remote Sens.* **2021**, *13*, 1095. [CrossRef]
3. Abrahamczyk, L.; Penava, D.; Markušić, S.; Stanko, D.; Luqman Hasan, P.; Haweyou, M.; Schwarz, J. Die Magnitude 6,4—Erdbeben in Albanien und Kroatien—Ingenieuranalyse der Erdbebenschäden und Erfahrungswerte für die Baunormung. *Bautechnik* **2022**, *99*, 18–30. [CrossRef]
4. Abrahamczyk, L.; Penava, D.; Markušić, S.; Stanko, D.; Luqman Hasan, P.; Haweyou, M.; Schwarz, J. Die Magnitude 6,4—Erdbeben in Albanien und Kroatien—Ingenieuranalyse der Erdbebenschäden und Erfahrungswerte für die Baunormung. *Mauerwerk* **2022**, *26*, 109–121. [CrossRef]
5. Atalić, J.; Uroš, M.; Šavor Novak, M.; Demšić, M.; Nastev, M. The Mw5.4 Zagreb (Croatia) Earthquake of 22 March 2020: Impacts and Response. *Bull. Earthq. Eng.* **2021**, *19*, 3461–3489. [CrossRef]
6. Šavor Novak, M.; Uroš, M.; Atalić, J.; Herak, M.; Demšić, M.; Baniček, M.; Lazarević, D.; Bijelić, N.; Crnogorac, M.; Todorić, M. Zagreb Earthquake of 22 March 2020—Preliminary Report on Seismologic Aspects and Damage to Buildings. *J. Croat. Assoc. Civ. Eng.* **2020**, *72*, 869–893. [CrossRef]
7. Markušić, S.; Stanko, D.; Penava, D.; Trajber, D.; Šalić, R. Preliminary Observations on Historical Castle Trakošćan (Croatia) Performance under Recent ML $\geq$ 5.5 Earthquakes. *Geosciences* **2021**, *11*, 461. [CrossRef]
8. Ožić, K.; Skejić, D.; Lukačević, I.; Stepinac, M. Value of Information Analysis for the Post-Earthquake Assessment of Existing Masonry Structures—Case Studies. *Buildings* **2023**, *13*, 144. [CrossRef]
9. Moretić, A.; Chieffo, N.; Stepinac, M.; Lourenço, P.B. Vulnerability Assessment of Historical Building Aggregates in Zagreb: Implementation of a Macroseismic Approach. *Bull. Earthq. Eng.* **2023**, *21*, 2045–2065. [CrossRef]
10. Predari, G.; Stefanini, L.; Marinković, M.; Stepinac, M.; Brzev, S. Adriseismic Methodology for Expeditious Seismic Assessment of Unreinforced Masonry Buildings. *Buildings* **2023**, *13*, 344. [CrossRef]
11. Markušić, S.; Herak, D.; Ivančić, I.; Sović, I.; Herak, M.; Prelogović, E. Seismicity of Croatia in the Period 1993–1996 and the Ston-Slano Earthquake of 1996. *Geofizika* **1998**, *15*, 83–101.
12. Herak, M.; Herak, D.; Markušić, S. Revision of the Earthquake Catalogue and Seismicity of Croatia, 1908–1992. *Terra Nov.* **1996**, *8*, 86–94. [CrossRef]
13. Aničić, D.; Steinman, V. Seismic Strengthening of Rector's Palace in Dubrovnik. In *Proceedings of the Scientst' Gatherings. The Balkan Cultural Heritage and Seismic Problems*; Proceedings; Mijušković, S., Ed.; Montenegrin Academy of Sciences and Arts (in Croatian: Crnogorska Akademija Nauka i Umjetnosti): Titograd, Montenegro, 1983; Volume 10, pp. 209–224.
14. Institute for the Restoration of Dubrovnik (in Croatian: Zavod za Obnovu Dubrovnika). Available online: https://zod.hr/ (accessed on 29 May 2023).
15. Herak, M.; Allegretti, I.; Herak, D.; Ivančić, I.; Kuk, V.; Marić, K.; Markušić, S.; Sović, I. Earthquake Hazard Maps of Republic of Croatia (in Croatian: Karte Potresnih Područja Republike Hrvatske). Available online: http://seizkarta.gfz.hr/karta.php (accessed on 5 February 2021).
16. Assembly of the Municipality of Dubrovnik Decision on the Organization and Functioning of the Institute for the Restoration. In *Original: Odluka o Organiziranju i Funkcioniranju Zavoda za Obnovu*; Assembly of the Municipality of Dubrovnik: Dubrovnik, Croatia, 1979.
17. Assembly of the Municipality of Dubrovnik Decision Amending the Decision on the Organization and Functioning of the Institute for the Restoration. In *Original: Odluka o Izmjenama i Dopunama Odluke Organiziranju i Funkcioniranju Zavoda za Obnovu*; Assembly of the Municipality of Dubrovnik: Dubrovnik, Croatia, 1980.
18. *Assembly of the Municipality of Dubrovnik Decision on Collecting Additional Funds for the Restoration of Cultural Monuments in the Area of Dubrovnik Municipality Damaged in the Earthquake of 15 April 1979*; Assembly of the Municipality of Dubrovnik: Dubrovnik, Croatia, 1982.

19. *Assembly of the Municipality of Dubrovnik Decision Amending the Decision on Collecting Additional Funds for the Restoration of Cultural Monuments in the Area of Dubrovnik Municipality Damaged in the Earthquake of 15 April 1979*; Assembly of the Municipality of Dubrovnik: Dubrovnik, Croatia, 1982.
20. Parliament of the Socialist Republic of Croatia. *Law on the Restoration of the Endangered Monumental Complex of Dubrovnik*; Assembly of the Municipality of Dubrovnik: Dubrovnik, Croatia, 1986.
21. *Assembly of the Municipality of Dubrovnik Decision on Financing the Restoration of the Endangered Dubrovnik Monument Complex*; Assembly of the Municipality of Dubrovnik: Dubrovnik, Croatia, 1986.
22. Socialist Federal Republic of Yugoslavia (FRY). Ordinance on Technical Standards for the Construction of High-Rise Buildings in Seismic Areas. In *Croatian: Pravilnik o Tehničkim Normativima za Izgradnju Objekata Visokogradnje u Seizmičkim Područjima*; Official Journal No. 31/81, 49/82, 29/83, 20/88, 52/90 (in Croatian: Službeni List SFRJ 31/81, 49/82, 29/83, 20/88, 52/90); Sluzbeni List SFRJ: Belgrade, Serbia, 1981.
23. *CEN ENV 1996-1-1*; Eurocode 6: Design of Masonry Structures—Part 1-1: General Rules for Buildings–Rules for Reinforced and Unreinforced Masonry. Uropean Committee for Standardization (CEN): Brussels, Belgium, 1995.
24. *EN 1996-1-1*; Eurocode 6: Design of Masonry Structures—Part 1-1: General Rules for Reinforced and Unreinforced Masonry Structures. European Committee for Standardization: Brussels, Belgium, 2005.
25. *EN 1998-1*; Eurocode 8: Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings. European Committee for Standardization: Brussels, Belgium, 2004.
26. Stanko, D.; Korbar, T.; Markušić, S. Evaluation of the Local Site Effects and Their Implication to the Seismic Risk of the UNESCO World Heritage Site Old City of Dubrovnik (Croatia). *J. Earthq. Eng.* **2023**, 1–29. [CrossRef]
27. Grünthal, G.; Musson, R.M.W.; Schwarz, J.; Stucchi, M. *European Macroseismic Scale 1998*; European Commission Publication Office: Luxembourg, 1998.
28. Ma, Y.; Wu, Z.; Liu, Z.; Zhang, M.; Aibaidula, M. Seismic Fragility Analysis of Aqueduct Structural Systems Based on G-PCM Method. *Sustainability* **2022**, *14*, 13161. [CrossRef]
29. Liu, C.; Fang, D.; Zhao, L.; Zhou, J. Seismic Fragility Estimates of Steel Diagrid Structure with Performance-Based Tests for High-Rise Buildings. *J. Build. Eng.* **2022**, *52*, 104459. [CrossRef]
30. *EN 1992-1-1*; Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings (EN 1992-1-1:2004). European Committee for Standardization: Brussels, Belgium, 2004.
31. Ademović, N.; Hadzima-Nyarko, M.; Pavić, G. *Advanced Technologies, Systems, and Applications III*; Avdaković, S., Ed.; Lecture Notes in Networks and Systems; Springer International Publishing: Cham, Switzerland, 2019; Volume 60, ISBN 978-3-030-02576-2.
32. Hadzima-Nyarko, M.; Mišetić, V.; Morić, D. Seismic Vulnerability Assessment of an Old Historical Masonry Building in Osijek, Croatia, Using Damage Index. *J. Cult. Herit.* **2017**, *28*, 140–150. [CrossRef]
33. Kuhlmann, W.; Butenweg, C.; Meskouris, K. Baudynamische Untersuchung Des Aachener Doms Unter Erdbebenbelastung. *Bautechnik* **2003**, *80*, 675–684. [CrossRef]
34. Taliercio, A.; Binda, L. On the Reliability of Linear Elastic Analyses of Historical Masonrybuildings: A Case Study. *J. Build. Apprais.* **2007**, *2*, 301–312. [CrossRef]
35. Lourenço, P.B.; Ramos, L.F.; Vasconcelos, G.; Peña, F. Monastery of Salzedas (Portugal): Intervention in the Cloister and Information Management. In *Proceedings of the VI International Conference on Structural Analysis of Historic Construction SAHC08*; D'Ayala, D., Fodde, E., Eds.; CRC Press: Bath, UK, 2008; pp. 95–108.
36. Doganer, S. Structural Preservation and Representation of Cultural Heritage. In Proceedings of the Re-De) Construction in Architecture—Livenarch 4th International Congress, Trabzon, Turkey, 9–11 July 2009; pp. 1109–1120.
37. Uzair, A.; Abrahamczyk, L.; Vrban, A.; Penava, D. Seismic Performance Assessment of the 18th Century Jesuit College in Dubrovnik's Old City. *Buildings* **2023**, *13*, 1904. [CrossRef]
38. Performance-Based Approach to the Earthquake Protection of Cultural Heritage in European and Mediterranean Countries | PERPETUATE | Project | News & Multimedia | FP7 | CORDIS | European Commission. Available online: https://cordis.europa.eu/project/id/244229/reporting (accessed on 1 September 2023).
39. Puncello, I.; Caprili, S. Seismic Assessment of Historical Masonry Buildings at Different Scale Levels: A Review. *Appl. Sci.* **2023**, *13*, 1941. [CrossRef]
40. Cantatore, E.; Esposito, D.; Sonnessa, A. Mapping the Multi-Vulnerabilities of Outdoor Places to Enhance the Resilience of Historic Urban Districts: The Case of the Apulian Region Exposed to Slow and Rapid-Onset Disasters. *Sustainability* **2023**, *15*, 14248. [CrossRef]
41. Ciantelli, C.; Arroyo Duarte, S.I.; Vaccaro, C.; Bonazza, A. Characterization of the Stone Masonries and Evaluation of the Environmental Impact in Panamá Viejo: A Contribution for the Conservation of the Monumental Complex. *Heritage* **2023**, *6*, 6526–6546. [CrossRef]
42. Thomoglou, A.K.; Jagadesh, P.; Voutetaki, M.E. Review of Out-of-Plane Strengthening Techniques of Unreinforced Masonry Walls. *Fibers* **2023**, *11*, 78. [CrossRef]
43. Luino, F.; Barriendos, M.; Gizzi, F.T.; Glaser, R.; Gruetzner, C.; Palmieri, W.; Porfido, S.; Sangster, H.; Turconi, L. Historical Data for Natural Hazard Risk Mitigation and Land Use Planning. *Land* **2023**, *12*, 1777. [CrossRef]
44. He, D.; Hu, J.; Zhang, J. Assessment of Sustainable Development Suitability in Linear Cultural Heritage—A Case of Beijing Great Wall Cultural Belt. *Land* **2023**, *12*, 1761. [CrossRef]

45. Procentese, F.; Gatti, F. Valorizing Community Identity and Social Places to Implement Participatory Processes in San Giovanni a Teduccio (Naples, Italy). *Sustainability* **2023**, *15*, 14216. [CrossRef]
46. Zirufo-Briones, B.V.; Pelegrín-Entenza, N. Model for the Strategic Governance of the Integrated and Sustainable Local Development of the Portoviejo Canton in the Province of Manabí, Ecuador. *Sustainability* **2023**, *15*, 14136. [CrossRef]
47. Knežević, S. *The Restoration of Dubrovnik 1979–1989 (in Croatian: Obnova Dubrovnika 1979–1989)*; Zavod za obnovu Dubrovnika: Dubrovnik, Croatia, 1989.
48. Jemo, I.; Brigović, N. *The Restoration of Dubrovnik. The Catalogue of Works in the Historic Centre of Dubrovnik from 1979 till 2009*; Institute for the Restoration of Dubrovnik (in Croatian: Zavod za obnovu Dubrovnika): Dubrovnik, Croatia, 2009; ISBN 978-953-55993-0-2.
49. Old City of Dubrovnik—UNESCO. World Heritage Centre. Available online: https://whc.unesco.org/en/list/95/ (accessed on 29 May 2023).
50. Herak, M.; Allegretti, I.; Herak, D.; Kuk, K.; Kuk, V.; Marić, K.; Markušić, S.; Stipčević, J. HVSR of Ambient Noise in Ston (Croatia): Comparison with Theoretical Spectra and with the Damage Distribution after the 1996 Ston-Slano Earthquake. *Bull. Earthq. Eng.* **2010**, *8*, 483–499. [CrossRef]
51. Herak, M.; Orlić, M.; Kunovec Varga, M. Did the Makarska Earthquake of 1962 Generate a Tsunami in the Central Adriatic Archipelago? *J. Geodyn.* **2001**, *31*, 71–86. [CrossRef]
52. Herak, D.; Herak, M. *Seizmičnost i Potrersna Opasnost na Makarskom Primorju*; Institut Društvenih Znanosti Ivo Pilar: Zagreb, Croatia, 2012.
53. Hrstić, I. *Zbivanja na Makarskom Primorju Tijekom i Nakon Potresa 1962. Godine*; Institut Društvenih Znanosti Ivo Pilar: Zagreb, Croatia, 2012.
54. Morić, D. Seismic Resistance of Stone Masonry Buildings Regarding Permissible Retrofitting Measures on Floor Structures. Ph.D. Thesis, University of Zagreb, Zagreb, Croatia, 1998.
55. Morić, D. *Floor Structures and Seismic Resistance of Cultural Heritage Stone Masonry Buildings*; Osijek Faculty of Civil Engineering Osijek, Josip Juraj Strossmayer University: Osijek, Croatia, 2003; ISBN 953-6962-05-5.
56. Turnšek, V.; Čačković, F. Some Experimental Results on the Strength of Masonry Walls. In Proceedings of the Second International Brick Masonry Conference, Stoke-on-Trent, UK, 12–15 April 1970; pp. 149–156.
57. Turnšek, V.; Terčelj, S.; Sheppard, P.; Tomažević, M. The Seismic Resistance of Stone-Masonry Walls and Buildings. In Proceedings of the 6th ECEE Conference, Dubrovnik, Croatia, 20 June 1978; The European Association for Earthquake Engineering—EAEE: Dubrovnik, Croatia, 1978; pp. 255–262.
58. Aničić, D.; Tomažević, M. Design and Analysis of Masonry Buildings, Part 1 (in Original: Konstruiranje i proračun zidanih zgrada, Dio 1.). In *Construction calendar (in Croatian: Građevinski kalendar)*; Associtaion of Civil Engineers and Technicians of Yugoslavia (in Croatian: Savez Građevinskih Inženjera i Tehničara Jugoslavije): Beograd, Serbia, 1990.
59. Aničić, D.; Tomažević, M. Design and Analysis of Masonry Buildings, Part 2 (in Original: Konstruiranje i proračun zidanih zgrada, Dio 2.). In *Construction Calendar (In Croatian: Građevinski Kalendar)*; Associtaion of Civil Engineers and Technicians of Yugoslavia (in Croatian: Savez Građevinskih Inženjera i Tehničara Jugoslavije): Beograd, Serbia, 1991.
60. Tomažević, M.; Sheppard, P. Revitalization of Stone Masonry Buildings from the Aspect of Their Seismic Protection. In *Proceedings of the Scientst' Gatherings*; The Balkan Cultural Heritage and Seismic Problems. Proceedings; Mijušković, S., Ed.; Montenegrin Academy of Sciences and Arts (in Croatian: Crnogorska Akademija Nauka i Umjetnosti): Titograd, Montenegro, 1983; Volume 10, pp. 184–198.
61. Stanković, V. Experimental Tests of Stone Walls in the Old Town of Budva (in Croatian: Eksperimentalna Ispitivanja Zidova Od Kamena u Starom Gradu Budva). In *Proceedings of the IV Kongres SDSGJ*; Savez Društava za Seizmičko Građevinarstvo Jugoslavije—SDSGJ: Cavtat, Croatia, 1986; pp. 99–106.
62. Sheppard, P.; Tomažević, M. In-Situe Tests of Structural Capacity of Old Masonry Buildings (in Croatian: In-Situ Ispitivanja Nosivosti Zidova Starih Zidanih Zgrada. In *Proceedings of the IV Kongres SDSGJ*; Savez Društava za Seizmičko Građevinarstvo Jugoslavije—SDSGJ: Cavtat, Croatia, 1986; pp. 85–92.
63. Aničić, D.; Sorić, Z.; Morić, D.; Macan, H. Mechanical Properties of Stone Masonry Walls. In *Proceedings of the Structural Repairs and Maintenance of Historical Buildings, STREMA*; Brebbia, C.A., Ed.; Computational Mechanics Publications, Suthampton: Florence, Italy, 1989; pp. 96–102.
64. Tomažević, M.; Velechovski, T.; Weiss, P. Experimental Study of the Influence of Structural Foundations and Reinforcement on the Behavior of Masonry Buildings During an Earthquake (in Slovenian: Eksperimentalna Študija Vpliva Konstrukcijske Zasnove in Armature Na Obnašanje Zidanih Zgradb Med Potr. In *Proceedings of the V Kongres SDSGJ*; Savez Društava za Seizmičko Građevinarstvo Jugoslavije—SDSGJ: Bled, Slovenia, 1990; pp. 121–130.
65. Aničić, D.; Steinman, V. *Knežev Dvor Dubrovnik, Glavni Projekt Sanacije, Konstrukterski Projekt, 21-641/81*; Civil Engineering Institute: Zagreb, Croatia, 1981.
66. Aničić, D.; Sorić, Z.; Morić, D.; Macan, H. Report 21-842/88 Investigation of Structural Characteristics of Stone Masonry Walls. In *Original: Istraživanje Nosivosti Kamenih Zidova*; Civil Engineering Institute: Zagreb, Croatia, 1988.
67. Petrovski, J.; Jurukovski, D.; Bojadžiev, M. Defining Basic Frequencies at the Rector's Palace Building by Measuring Ambient Vibrations. Report IZIIS 81-34. In *Original: Definisanje Osnovnih Frekvencija Na Objektu Knežev Dvor Mjerenjem Ambijent Vribracija (Izveštaj IZIIS 81-34)*; Institute of Earthquake Engineering and Engineering Seismology (IZIIS): Skopje, Macedonia, 1981.

68. Niederwanger, G. Measurement and Estimation of Vibration of Old Buildings. In *Proceedings of the Structural Studies, Repairs, and Maintenance of Historical Buildings VI*; Brebbia, C.A., Jaga, W., Eds.; WIT Press: Southampton, UK, 1999; pp. 67–76.
69. CEN. *Eurocode: Basis of Structural Design (EN 1990:2002+A1:2005+A1:2005/AC:2010)*; CEN: Brussels, Belgium, 2010.
70. SCIA. Your Partner in Structural Engineering & Design. Available online: https://www.scia.net/en (accessed on 11 June 2023).
71. EN. *Eurocode: Basis of Structural Design—National Annex (HRN EN 1990:2011/NA:2011)*; European Committee for Standardization: Brussels, Belgium, 2011.
72. CEN. *Eurocode 8: Design of Structures for Earthquake Resistance—Part 3: Assessment and Retrofitting of Buildings (EN 1998-3:2005+AC:2010)*; European Committee for Standardization, Ed.; European Committee for Standardization: Brussels, Belgium, 2010.
73. Ministry of Physichal Planning Construction and State Assets. *Tehnički Propis o Izmjenama i Dopunama Tehničkog Propisa za Građevinske Konstrukcije*; Ministry of Physichal Planning Construction and State Assets: Zagreb, Croatia, 2022.
74. Miraglia, G.; Petrovic, M.; Abbiati, G.; Mojsilovic, N.; Stojadinovic, B. A Model-order Reduction Framework for Hybrid Simulation Based on Component-mode Synthesis. *Earthq. Eng. Struct. Dyn.* **2020**, *49*, 737–753. [CrossRef]
75. Roumelioti, Z. Stochastic Simulation of Strong-Motion Records from the 15 April 1979 (M 7.1) Montenegro Earthquake. *Bull. Seismol. Soc. Am.* **2002**, *92*, 1095–1101. [CrossRef]
76. Lu, B.; Zhu, J.; Ge, Y.; Chen, Q.; Wen, Z.; Liu, G.; Li, L. Automated Determination of the Volume of Loose Engineering Deposits Using Terrestrial Laser Scanning. *Remote Sens.* **2023**, *15*, 4604. [CrossRef]
77. Valente, M. Earthquake Response and Damage Patterns Assessment of Two Historical Masonry Churches with Bell Tower. *Eng. Fail. Anal.* **2023**, *151*, 107418. [CrossRef]
78. Valente, M. Seismic Behavior and Damage Assessment of Two Historical Fortified Masonry Palaces with Corner Towers. *Eng. Fail. Anal.* **2022**, *134*, 106003. [CrossRef]
79. Bui, T.T.; Limam, A.; Sarhosis, V.; Hjiaj, M. Discrete Element Modelling of the In-Plane and out-of-Plane Behaviour of Dry-Joint Masonry Wall Constructions. *Eng. Struct.* **2017**, *136*, 277–294. [CrossRef]
80. Sarhosis, V.; Bagi, K.; Lemos, J.V.; Milani, G. (Eds.) *Computational Modeling of Masonry Structures Using the Discrete Element Method*; Advances in Civil and Industrial Engineering; IGI Global: Hershey, PA, USA, 2016; ISBN 9781522502319.