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Seismic upgrading of cultural heritage – A case study using an educational building in Croatia from the historicism style

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A R T I C L E I N F O

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A B S T R A C T

More than two years have passed since the devastating earthquakes struck Croatia in 2020, in which many educational buildings were damaged. In addition, several damaged educational buildings are under heritage protection, representing a special challenge for civil engineers during structural renovation. Strengthening methods that achieve adequate level of seismic capacity are limited in order to preserve the identity of these buildings. In the manuscript, a short overview of the damage to the educational sector is given with a special focus on a renovation of one case study. The case study is an educational building with a masonry structure located in the Lower Town of Zagreb and from the 19th century. An assessment of the structural condition was performed and a model was developed in the 3Muri software. Three variants of strengthening methods were applied to the model – FRCM, shotcrete and a combination of FRCM and shotcrete. Finally, each variant model was analyzed using the pushover method. The results are compared in terms of achieved earthquake capacity, expected cost and environmental impact.

1. Introduction

In the morning hours of March 22, 2020, half an hour apart, the Croatian capital was hit by two earthquakes of moderate magnitude, measuring 5.5 and 5.0 on the Richter scale [1]. The intensity maps are shown in Fig. 1. The earthquake series caused the death of a 15-year-old girl and the city suffered enormous material damage, especially in the vicinity of the epicenter and in the city center, which has exceptional cultural and historical significance. A mitigating circumstance is that the earthquake occurred during the COVID-19 epidemic when social activities were reduced to a minimum (thus people agglomeration), otherwise the number of human casualties would have been much higher. As there was no defined official post-earthquake form for building inspections in Croatia, a form based on the Italian experience was adapted to the conditions in Croatia [2]. After a preliminary inspection, the buildings were assigned one of six possible usability labels. Green label represents buildings usable without limitations (U1) and buildings usable with specific recommendations (U2). Yellow label stands for temporary unusable buildings in need for a detailed inspection (PN1) or emergency interventions (PN2). Red label represents buildings unusable due to external impact of falling debris (N1) or own damage (N2).

The March 2020 earthquake affected one-fifth of the housing stock and critical infrastructure buildings such as schools, hospitals and buildings crucial to the functioning of the state. It was mostly minor to moderate structural damage. The Croatian government and

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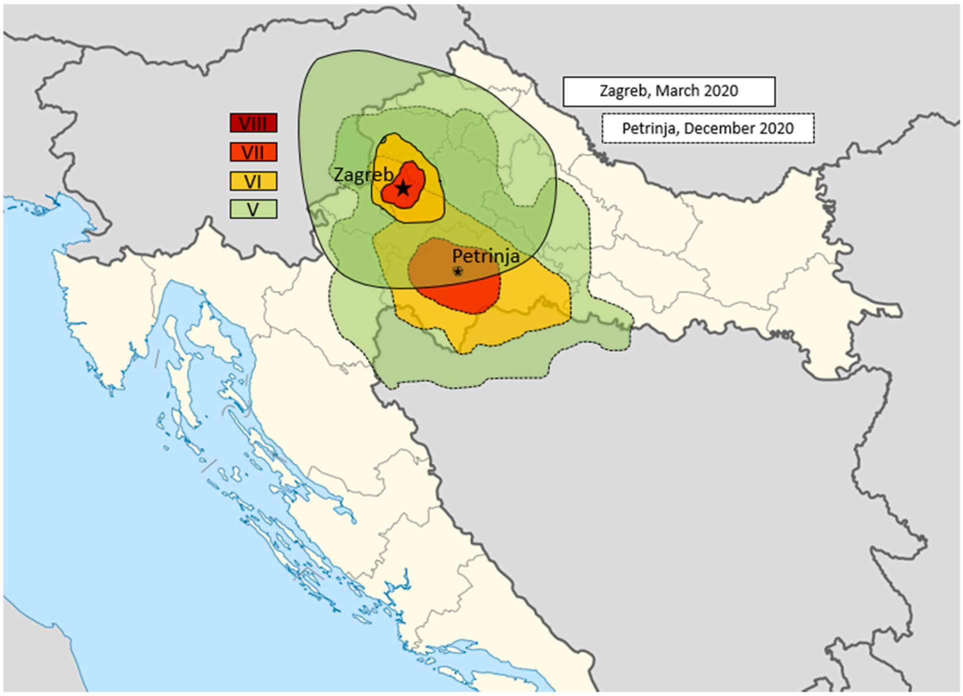


Fig. 1. Intensity maps for earthquakes in Croatia, 2020 (EMS-98 scale).

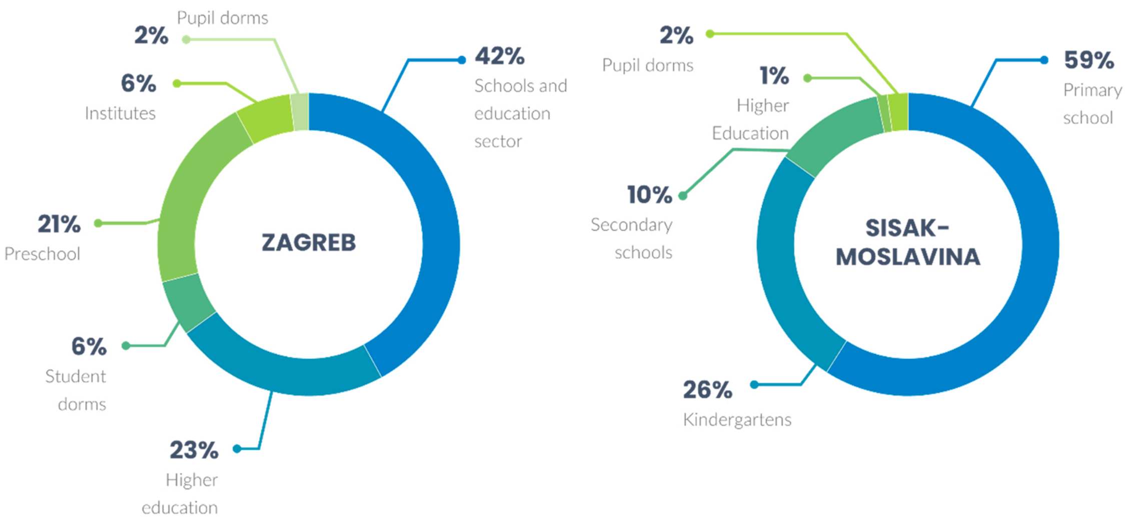


Fig. 2. Damaged buildings of the education sector in the 2020 Croatia earthquakes and two different regions [3,4].

the World Bank have estimated the damage at 11,3 billion euro, partly due to a large number of damaged buildings with cultural heritage status, which are present in the housing, health, education, culture and business sectors [3]. Approximately 10% of damaged buildings in Zagreb belong to the education sector, in various typologies (Fig. 2, left). Moderate damage was recorded in 160 buildings, while 12 buildings suffered significant damage. A scenario similar to the one in Zagreb was repeated in December 2020 in the Sisak-Moslavina County (Fig. 2, right). An earthquake measuring 6.4 on the Richter scale with an epicenter 3 km southwest of Petrinja was recorded. At that point, already well-trained engineers carried out preliminary usability assessments. The building stock (unreinforced masonry, degraded condition) and the damage are similar to those in Zagreb. The value of estimated damage is 5,5 billion euros [4]. In total 271 educational buildings were assessed after the earthquake, and 29 exhibited moderate damage, while significant damage was reported at 19 buildings, Additional damage was caused by soil liquefaction.

Buildings with the status of cultural heritage are mostly for public use, so the assessment and conservation of such buildings are extremely important, not only due to the preservation of the cultural identity but also due to the large number of users. These are

Table 1
Renovation levels [10].

	Level 1	Level 2	Level 3	Level 4
Return period (year)	–	95	225	475
Limit state	–	Damage limitation	Significant damage	Significant damage
Resistance level	Initial resistance	Increased resistance	Increased resistance	Increased resistance
Applicable to	All buildings	Residential and office buildings, public buildings with minor damage	Educational buildings, public buildings with moderate damage	Health facilities of high importance, emergency services buildings

Fig. 3. South and north façade of the case study building.

mainly traditional masonry structures with wooden floor and roof structures. The damage occurred mostly due to stiffness variability, weak or non-existent connections and poor connection to the floor or roof structures. Long-term use of buildings, together with infrequent and poor maintenance, have caused material degradation. The most common damage is related to the collapse of chimneys, gable walls and roofs [1,2].

It is questionable why earthquakes of moderate magnitude caused disproportionately severe damage. One aspect is that Croatia is placed in a seismically active zone but the public awareness of earthquakes is very low, as evidenced by poor quality and illegal construction (900,000 requests for legalization) and undocumented reconstructions. It should be emphasized that many buildings in Zagreb were built before the existence of any standards for earthquake resistance design. The first such standards were issued in former Yugoslavia in 1964 [5,6] but the level of seismic action defined in these standards is up to several times lower than the level defined by the National Annex in Eurocode EN 1998–1–1 [7]. Another paradox is that buildings that do not have sufficient seismic capacity, i.e., are in need for structural strengthening, have participated in energy renovation co-financed by the European Union [8]. An additional problem is the lack of knowledge about seismic risk [9] (seismic hazard, vulnerability and exposure of the building stock). Namely, Croatia still does not have a GIS information platform (number of users, purpose of buildings, year of construction, structural system, etc.) defining exposure and vulnerability of national building stock.

A few contradictions occurred after the Zagreb earthquake, the Law on Reconstruction by Earthquake-Damaged Buildings in the City of Zagreb, Krapina-Zagorje County and Zagreb County [10] was passed six months after the earthquake, which slowed down the reconstruction process. Among others, the law defines four renovation levels, depending on the degree of damage, the purpose of the building and the financial capabilities of the investor. Level 1 refers to re-establishing the initial resistance of the structure as it had before the earthquake, while levels 2, 3 and 4 achieve satisfactory earthquake resistance for the reference return period (Table 1). According to the law [10], 60% of the costs are borne by the Republic of Croatia from the state budget, 20% by the counties, and the remaining 20% by the owners, except finishings (installation of façade, parquet, plastering, painting…) which are not included but financed entirely by owners. Current market situation - rising material price and labor shortage - adversely affects the investors. Moreover, only owners of buildings that have been assigned with "temporarily unusable" or "unusable" labels during the preliminary assessment of usability are entitled to co-financing. Due to the subjectivity of civil engineers during the inspection, some buildings with similar level of damage received different labels, meaning that some owners were denied financial aid. A special omission of the law is the renovation of isolated apartment buildings and buildings in an aggregate, which are not renovated as a single unit but individually. Also, the law applies to legalized properties, leaving innumerous damaged illegal properties behind.

In this paper, one damaged educational building will be presented as a case study of the process that followed the earthquake. A brief explanation of the building's damage is shown first. The focus of the paper is, however, to show different strengthening strategies and their influence on seismic resistance and the cost of the works.

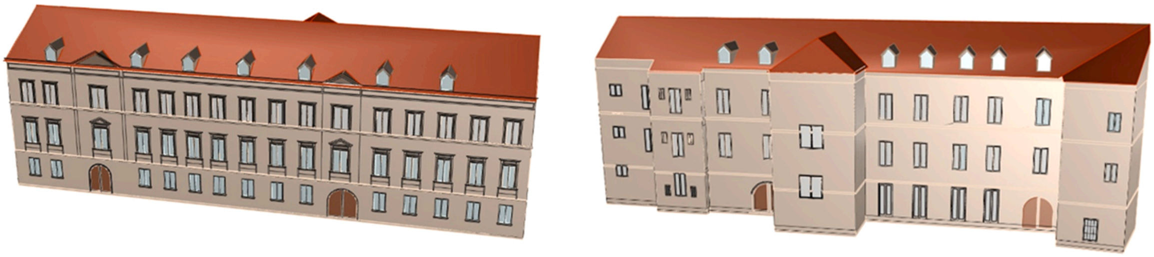
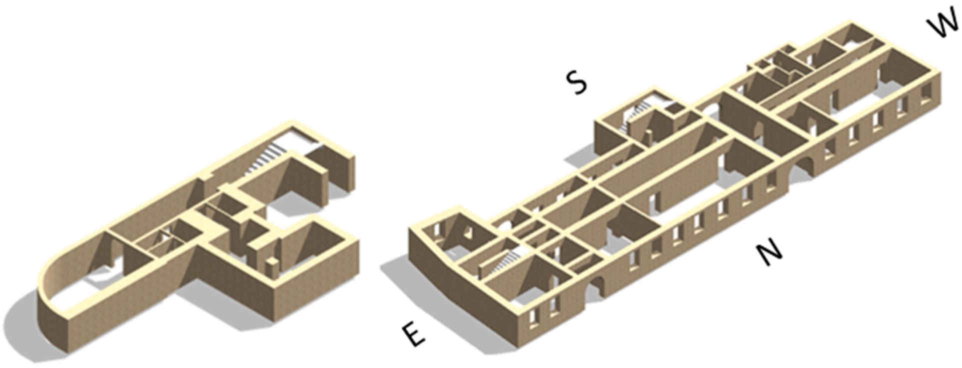


Fig. 4. Model created in Rhinoceros 3D software.



a) (b)

Fig. 5. 3D view created in Allplan software (a) basement (b) ground floor.

Fig. 6. Characteristic cracks, marked with a red line (photo credit: Mislav Stepinac).

2. Description of the case study

The focus of this paper is an educational building with the status of cultural heritage located in the Lower Town of Zagreb (Figs. 3, 4). The building was constructed in the 19th century and served as a boys' seminary. Originally it was a single-story building but it was upgraded later. The last reconstruction was in 1997. Nowadays, the building is used as a higher education institution. Prior to the earthquake, the building was regularly maintained.

The building has a rectangular floor plan with dimensions of 12 × 53 m and two wings measuring 4.4 × 7.6 m and 4.2 × 5.4 m (Fig. 5). The building is constructed of brick elements 30 × 15×6.5 cm, and the thickness of the load-bearing walls decreases with increasing height, being 51, 43 and 28 cm for each story. It is stressed that the bricks were properly arranged across the thickness, making a single leaf wall. The thickness of the plaster also varies, from 3 cm to 6 cm. The building consists of a basement, ground floor, first, second floor and attic. Prior to the reconstruction in 1997, the basement and ground floor structures were masonry vaults, and, on the other floors, wooden beams were present. After the reconstruction on the ground floor, a semi-precast masonry/concrete floor

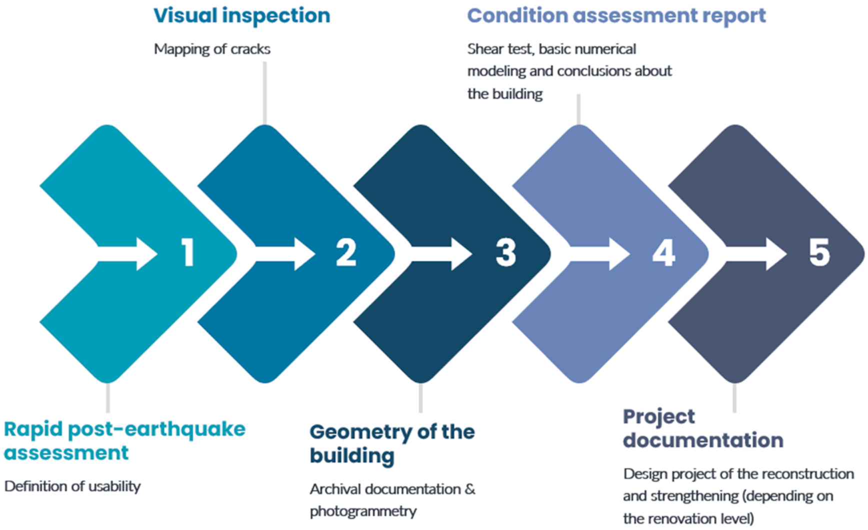


Fig. 7. Structural renovation process.

Fig. 8. Shear strength test of masonry [12].

system was inserted between the beams, the first and second floors were replaced with reinforced concrete slabs 12 and 16 cm thick. During the reconstruction, two reinforced concrete staircases were built at the ends, while the older central staircase is made of stone.

The day after the earthquake, a preliminary inspection of the building was performed [13,14]. Damage in the form of cracks on wall finishings, arches, vaults and ceilings was noted (Fig. 6). Local separation and decay of the plaster was detected. In the eastern part of the building, diagonal cracks are visible on the load-bearing walls. The central staircase suffered the most significant damage. The building was assigned a temporarily unusable label (PN1) and it was concluded that a detailed inspection is required. The use of the building is limited in places where there is a danger of plaster falling off. The use of the east and west staircases is limited by the number

Fig. 9. Photogrammetric view of the building, respectively with positions of the camera, photogrammetric model, measuring of the roof geometry, measuring of a crack, photo of a crack.

of users, while the central one is completely closed.

A few months later, a detailed examination was performed [14,15]. The flowchart of the performed activities is shown in Fig. 7. It was found that the cracks on the walls of the central staircase core coincide from the outside and inside, which indicates that the cracks are not superficial. The walls of the central core extend through the entire height of the building without any lateral restraints, and are weakened by openings, so they are considered to be the most critical part of the building. Cracks in the transverse walls of central core indicate possible out-of-plane failure of the mechanism. Shear strength testing of masonry were performed [14,15]using a hydraulic jack (Fig. 8). Visual inspection followed by in-situ examinations is explained in detail in [11]. It revealed that the masonry was in a good condition. Archival documentation was insufficient for geometry assessment. Photogrammetry was used to assess the true geometry of the building (Fig. 9)[16–18]. DJI Mavic 2 pro drone was used to take photos. Altogether, 87 photos were taken and the basic model was made in Agisoft Metashape software [19]. The full assessment of the presented case study was elaborated more in the detail in [11].

3. Structural strengthening

3.1. Strengthening methods

Croatian building stock, just like European, consists of a large number of unreinforced masonry structures (URM). In the past, masonry structures were mostly conceived to withstand vertical loads. Earthquakes which struck Croatia in 2020 have demonstrated that such structures do not have sufficient horizontal resistance. During an earthquake a great amount of energy is released which the structure dissipates by deformation and damage. There are two key masonry failure mechanisms: in-plane (shear or flexure) and out-of-plane (bending failure). The in-plane failure mechanism is the favorable one in terms of ductility and energy dissipation, in order to avoid activating the out-of-plane mechanism the structure must be originally designed or subsequently strengthened properly. The main disadvantage of old masonry structures is the poor connections between the walls and the floor structures, which causes the walls to behave independently. In order to achieve an integral "box effect", walls must be properly connected to new floor structures – flexible or rigid diaphragms [18]. It is possible to strengthen unreinforced masonry structures by adding reinforced concrete (RC) elements. Such retrofit approach, if adequately designed and implemented, will increase the strength and ductility which is related to the change of global deformed shape and failure mechanism [20]. This retrofit technique will only be effective if the floor structure is diaphragm in both directions. If the diaphragm is rigid, it distributes the horizontal load proportionately to the stiffness of the vertical elements. Since only a few concrete elements are added and much of the mass of URM buildings are in the walls, the total mass of the structure affecting the value of the inertial seismic force generally increases by less than 5%. If the existing floor structure consists of wooden beams, it can be coupled with a reinforced concrete slab or a cross laminated timber (CLT) floor. If the masonry structure is built without tied posts and lintels, they may be added to confine the masonry. Proper connections between walls and floor structures can be constructed by "L" shaped steel profiles or anchored steel bars. Connecting parallel walls with wooden beams or steel ties, properly anchored, also prevents out-of-plane failure mechanisms.

If a global behavior of the structure is achieved, masonry walls are usually prone to fail in one of two diagonal tension failure modes: stepped and straight mode. The stepped mode is a common failure mechanism for newly designed structures, while the straight mode is common for existing structures with rubble masonry. The repair method for cracks depends on the width and type of crack. If the crack width is less than 10 mm and if the wall thickness is relatively small, then it can be possibly filled with mortar (even if this is a complex and unreliable operation). If the wall is thick, a crack can be injected with grout. Walls with cracks larger than 10 mm are usually partially rebuilt. When rebuilding, it is necessary to provide temporary support for floor structures and walls above the

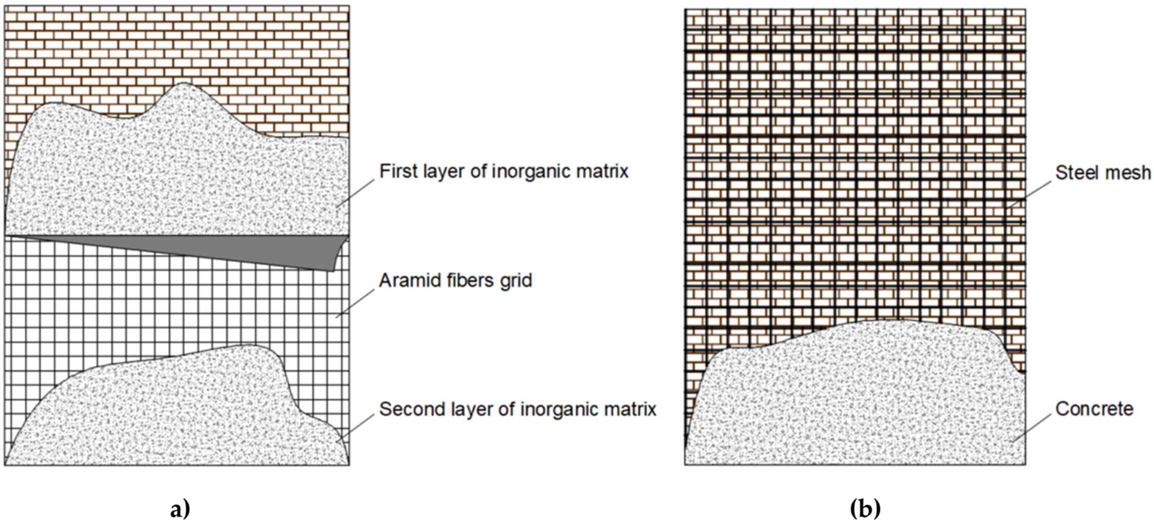


Fig. 10. (a) Application of FRCM (b) shotcreting.

damaged wall. If the damage is localized in the mortar, the retrofitting is done by partially removing the damaged mortar. That way, the resistance of masonry structures to vertical and horizontal loads increases.

Traditional strengthening techniques are not always an appropriate solution (injection grouting, wall cladding with reinforced plaster or jacketing, prestressing etc). For example, in buildings with cultural heritage status, these techniques may be too invasive. The Croatian Law on the Protection and Preservation of Cultural Heritage [21] determines that for the conservation of buildings that are individually protected cultural property or are located within a cultural-historical area, it is necessary to obtain the approval of the competent conservation department. The approval of the authorities ensures that the works will not damage the character and integrity of the historic building.

Less invasive strengthening techniques are considered to be the application of textile reinforced mortars (TRM) also known as fabric – reinforced cementitious matrix (FRCM) [22–24]. The composites consist of a fiber mesh with the function of reinforcement built into the matrix (Fig. 10a). Orientation and type of fibers, composition and amount of matrix and method of installation are factors that affect the characteristics of composites. The bond between the matrix and the fibers is achieved by impregnating the mortar in the gaps between the fiber mesh. The density of the mesh can be controlled independently for each direction, which affects the mechanical properties of the fabric and the bond with the matrix. The matrix transmits stresses from the masonry to the fibers and has the function of connecting and protecting the fibers from external influences. The mesh (fabric) made of fiber has the role of absorbing tensile stresses. The use of FRP is common for the mesh. Carbon [25], glass [26], basalt and aramid fibers are used. Fabric-reinforced cementitious mortar was created by replacing the organic binder, i.e., matrix, with an inorganic binder - cement or lime mortar [27]. Tests carried out on walls of brick or stone elements showed more favorable behavior in the plane and out of the plane [28] if the masonry was reinforced with the FRCM system instead of the FRP system [29]. FRCM system improves load-bearing capacity and deformation capacity. However, it should be taken into account that increasing the number of FRCM layers reduces the deformation capacity[30].

Strengthening methods must not only ensure sufficient level of structural capacity, but also aim for a sustainable solution. The main issue related to sustainability is the emission of carbon dioxide and energy consumption [31]. Many researchers have dealt with this issue and suggested solutions [32]. Recent research show that in combination with layers of thermal insulation, FRCM system is also an acceptable option for energy renovation [33,34]. In December 2020, the Government of the Republic of Croatia developed a long-term strategy for the renovation of the national fund of buildings until 2050. The strategy [35] supports the renewal of the national stock of residential and non-residential buildings, public and private ones, as well as the transformation of the existing building stock into an energy-efficient and decarbonized stock by 2050. Given all these advantages, the FRCM system may be a competitive solution, especially for buildings with cultural heritage status.

Shotcrete is applied in the case of increased horizontal action. Reinforcement is placed on one or both sides of the wall, on which shotcrete is applied (Fig. 10b). Linings placed on opposite faces of the masonry are connected by transverse reinforcement. One lining is connected to the wall with anchors. The thickness of the lining is usually 5–6 cm, and it can be up to 8 cm for more massive walls. This way, a larger cross-section is realized, which then has increased compressive, tensile and shear strength and ductility [36]. Due to this and ease of application, this method is very common in practice during reconstruction, but its invasiveness should also be considered.

3.2. Numerical modeling

The structure under study is modeled in *3Muri software.* The software was developed in Italy at the University of Genoa and is used

Table 2
PGA values.

Limit state	Return period (year)	Peak ground acceleration (m/s^2)
Near collapse	475	0.26 g
Significant damage	225	0.18 g
Damage limitation	95	0.13 g

Table 3
Masonry material characteristics.

Material characteristics	Value
Modulus of elasticity	3000 N/mm^2
Shear modulus	1200 N/mm^2
Specific weight	18 kN/m^3
Mean compressive strength	6,63 N/mm^2
Shear strength	0,14 N/mm^2
Characteristic compressive strength	5,53 N/mm^2

Table 4
FRCM system.

FRCM system						
Fiber thickness t_f (mm)	0.15	0.18	0.22	0.25	0.28	0.30
Fiber cross-sectional area (mm^2/m)	150	180	220	250	280	300
Modulus of elasticity E (N/mm^2)	60,000					

for static and seismic analysis of masonry structures. The advantage of this software is the calculation method *FME - Frame by Macro Element* that provides a better insight into the real behavior of the structure during seismic actions. There are three categories of macroelements: pier elements and wall elements which are deformable and connected by the third category of elements - rigid nodes [37].

The pushover method is a nonlinear static analysis performed for constant gravitational loads and monotonically increasing horizontal loads. It may be used for newly designed and existing structures to check or control overstrength, to estimate expected plastic mechanisms and distribution of damage, to assess the behavior of existing or renovated buildings according to EN 1998–3 [7]. The structure is subjected to vertical load and then loaded with the static lateral horizontal load which represents the inertial forces created by the action of the earthquake. Two forms of lateral load distribution are applied: uniform and modal. The lateral load is gradually increased until the limit state is reached. The procedure is performed until the displacement of the control node reaches 150% of the target displacement obtained based on the elastic response spectrum.

The value of peak ground acceleration for the building location is defined in the seismic hazard maps [38] from the National Annex to Eurocode 8: Design of Structures for Earthquake Resistance (Table 2). Since the case study is a building of exceptional cultural significance that is used as an educational institution, it is classified in the 3rd category of importance. In the software, the importance category is taken into account through the importance factor, whose value is $\gamma_I = 1.2$. Based on available data, soil type C (deep deposits of compacted or medium-compacted sand, gravel or hard clay with a thickness of several tens to hundreds of meters) can be assumed. Roof structures loads and material properties are derived from the original static design, and the slabs are considered rigid and base restraints are set as fixed. In 1997, floors were replaced with concrete slabs, therefore they are modeled as rigid diaphragms, which is the reason why only vertical members were strengthened. The box effect is respected with the mentioned concrete slabs. The walls were taken as adopted in 3Muri software and most analyses in which disintegration is not considered. It is stressed that the bricks were properly arranged across the thickness. The roof structure is not considered a load-bearing element in the model as it does not contribute significantly to the global resistance of the structure, but its mass was taken into account in the calculation of the seismic force. Lateral contact with other buildings was not taken into account. We consider that the results of "single" building are likely to be on the conservative side, as concluded in [39,40]. The real damage to the structure caused by the earthquake coincides with the damage to the model thus proving the reliability of *3Muri software*. The observed building was modeled as an isolated unit due to insufficient data on neighboring buildings. In order to roughly assess the effect of neighboring buildings on the observed building, the vulnerability index was used. The index is based on five categories depending on the height of the surrounding buildings, the position of the building in the unit, the mismatch of floor heights, differences in material characteristics between buildings and differences in the areas of openings on the facade walls [41,42]. According to the mentioned five parameters, the buildings in the aggregate have a minimal impact on the observed building, and it can be assumed that the modeling of the building as isolated as on the safe side.

Based on the real structural damage caused by the earthquake in March 2020 and the model damage simulated in software *3Muri*, it

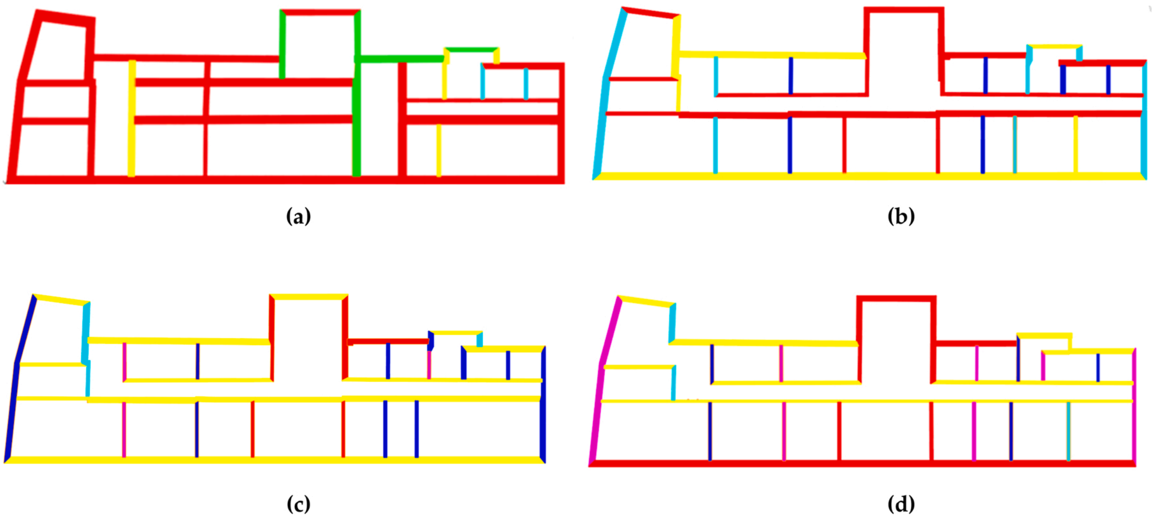


Fig. 11. FRCM system (a) ground floor plan (b) first floor plan (c) second floor plan (d) attic floor plan.

Table 5
Shotcrete and FRCM system strengthening.

FRCM system					
Fiber thickness t_f (mm)	0.15	0.18	0.22	0.25	0.28
Fiber cross-sectional area (mm²/m)	150	180	220	250	280
Modulus of elasticity E (N/mm²)			60,000		
Shotcrete					
Steel B500B					
Reinforcing mesh Q503					

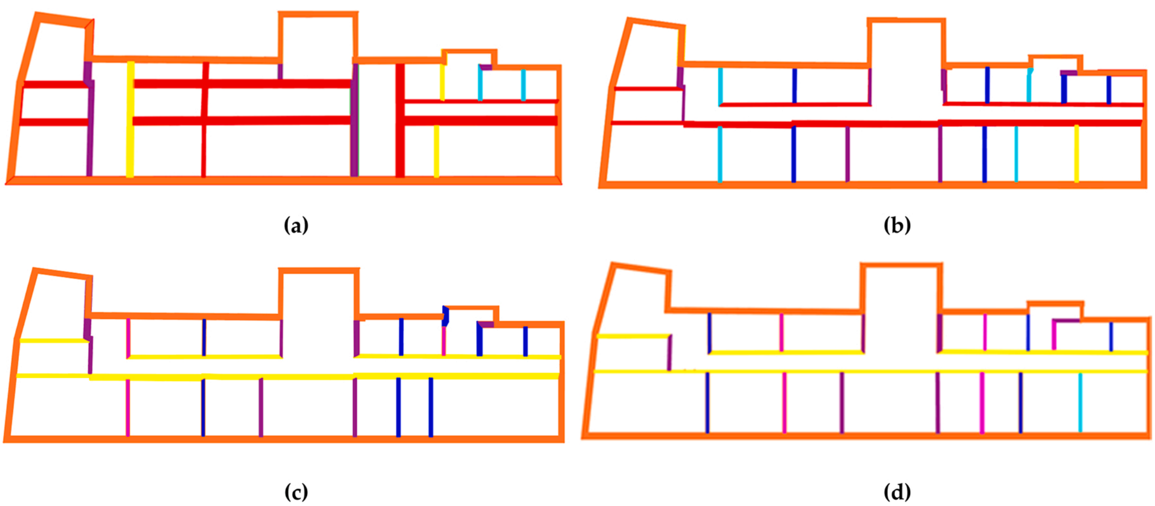


Fig. 12. Combination of FRCM system and shotcrete (a) ground floor plan (b) first floor plan (c) second floor plan (d) attic floor plan.

is not necessary to strengthen each element equally, nor is it economical. Masonry characteristics are shown in Table 3. For the first variant, the FRCM composite with aramid fibers was placed on both faces of the walls, 3 layers were used (Table 4, Fig. 11). FRCM with aramid fabric was used because it is common to use it in Croatia due to availability by the producers. FRCM-matrix was taken as it defined in the Italian code. The procedure was performed iteratively, the initial strengthening concept was corrected according to the

Table 6
Risk indices - a model strengthened by the FRCM system.

Limit state	α (x direction)	α (y direction)
Significant damage	1777	1085
Damage limitation	1508	1231

Table 7
Risk indices - a model strengthened by shotcrete.

Limit state	α (x direction)	α (y direction)
Significant damage	1897	1015
Significant damage	2283	1206
Damage limitation	2173	1569

Table 8
Risk indices - a model strengthened by FRCM systems and shotcrete.

Limit state	α (x direction)	α (y direction)
Significant damage	1551	1179
Damage limitation	1325	1305

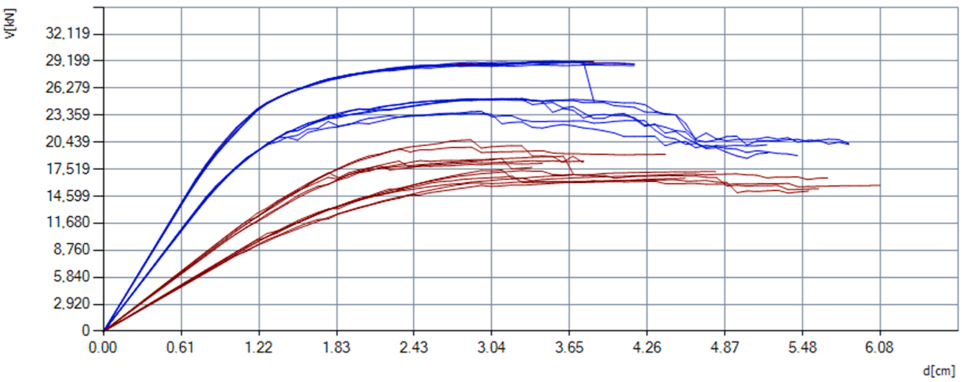


Fig. 13. Pushover curves for model strengthened by the FRCM system for x (blue) and y direction (red).

results of the analysis until the limit states of significant damage and damage limitation were met. Because of the iteration process, the walls were not strengthened equally but with strengthening which gives the best results, despite the stiffness difference. The obtained results are showing dominant translation at failure, so the stiffness difference is not having a large influence on the global behavior of the building. Moreover, the common principles of the new laws and regulations [10,21] in Croatia were respected.

For the strengthening variant in which shotcrete is used, Q503 reinforcement mesh, steel class B500B, has been selected. The mesh is composed of bars with a diameter of 8 mm with 10 cm spacing. Steel class B500B is a standard reinforcing steel, with yield strength of 500 MPa and B ductility class. Since the model whose façade walls were strengthened only on the inner face met all the required checks, such a solution has been accepted. On the remaining walls, the reinforcing mesh is placed on both faces. In this way, the external appearance of the building is not disturbed and the need for the use of scaffolding is reduced, which ultimately results in a lower cost of renovation. The authors are aware that the application of shotcrete with steel reinforcement is a controversial solution but, precisely because of this, it was considered. The capital of Croatia is at the moment being under major reconstruction and is going to be for a few years more at least. So far shotcrete is the most used technique, even in the case of historical construction. The authors estimate that at least 80% of the renovated buildings will be strengthened with concrete shotcreting. In this paper, the downside of this solution was highlighted and the advantages of less “popular” techniques among engineers in Croatia, and also across the world, were emphasized. Environmental impact at the end of the paper is going in favor of the mentioned statements.

In the last and third variant, a combination of shotcrete and FRCM system was used (Table 5, Fig. 12). The shotcrete was used on the façade walls and stairwell walls, while the FRCM system was used on the remaining interior walls. Reinforcement meshes Q503 were used for shotcrete application. On the façade walls, they are placed only on the inner face. On the inner walls of the central core and wings, the shotcrete is placed on both faces, because according to the calculations, they are the most critical parts of the building, and it is impossible to strengthen them on one side only. As for FRCM, five different systems were used. The composite is placed on both faces of the walls.

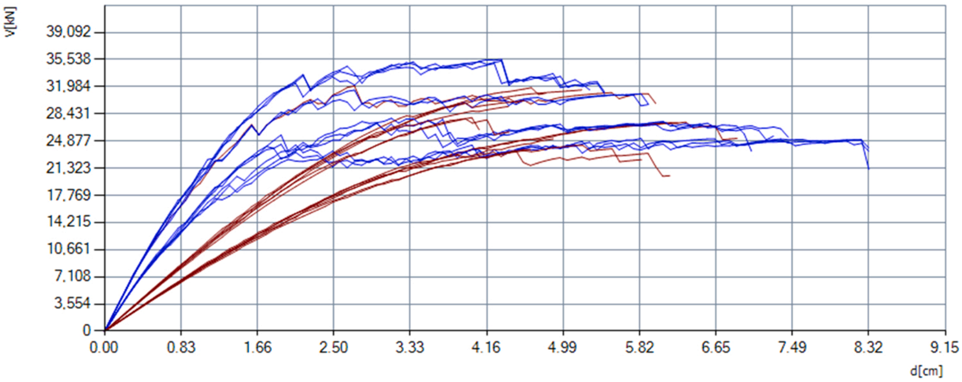


Fig. 14. Pushover curves for model strengthened by shotcrete for x (blue) and y direction (red).

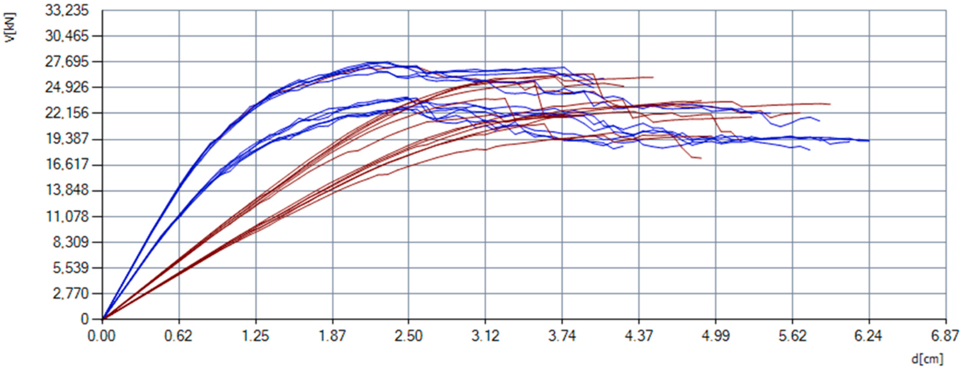


Fig. 15. Pushover curves for model strengthened by FRCM systems and shotcrete for x (blue) and y direction (red).

3.3. Results

For the limit states of significant and limited damage, 24 analyses were performed, including x and y direction, uniform and modal load distribution, and different eccentricity values. The control node is located on the fourth floor near the center of mass. The results of the analyses are presented using risk index α (Tables 6–8), damage visualizations and pushover curves (Figs. 13-16). The risk index is the ratio of capacity acceleration to peak ground acceleration, it needs to be calculated for each limit state. The limit state is considered satisfied if $\alpha > 1$. Approximate renovation costs were calculated for each variant (Tables 9–11).

Given that the building has the status of cultural heritage, the goal was to meet the limit states of significant and limited damage. By satisfying these limit states, seismic resistance was brought to level 3.

Risk indices vary for each direction, but if the average risk index is taken as the capacity indicator, it is reasonable to conclude that the strengthening by shotcrete is the most favorable variant (Figs. 17, 18).

Fig. 19 shows the comparison of strengthening variants considering capacity and renovation costs. Given that the requirements of sustainability in the construction sector are becoming more and more important, the approximate environmental impact was also calculated. The diameter of the circles represents the ratio of CO_2 emissions during the production of the required quantities of materials for each variant of strengthening. It must be noted that ratios do not include the emissions of CO_2 during the phases of transportation, construction, use and demolishing or recycling but only during the material production phase. Carbon dioxide emissions are calculated using software SimaPro [44]. The following values were taken (referring to climate change impact category only): 3,91 kg CO_2/kg fibers, 282 kg CO_2/m^3 concrete, 5,01 kg CO_2/kg steel (Table 12). Carbon cost in Croatia in 2020 was estimated to 25,6 €/t CO_2, while it is expected to increase to 93,1 €/t CO_2 by 2050 [45]. Total carbon costs for each strengthening variant are displayed in Fig. 20. Although the application of shotcrete is often used in practice and is the only variant by which the resistance of the structure is brought to the level 4 defined by the relevant codes, in this case, its invasiveness and environmental impact should not be neglected.

4. Conclusion

Earthquakes are extreme events, meaning that there is a low public awareness of their consequences. Nevertheless, earthquakes occur and cause great horizontal forces on structures. The impact of an earthquake includes namely economic damage, human

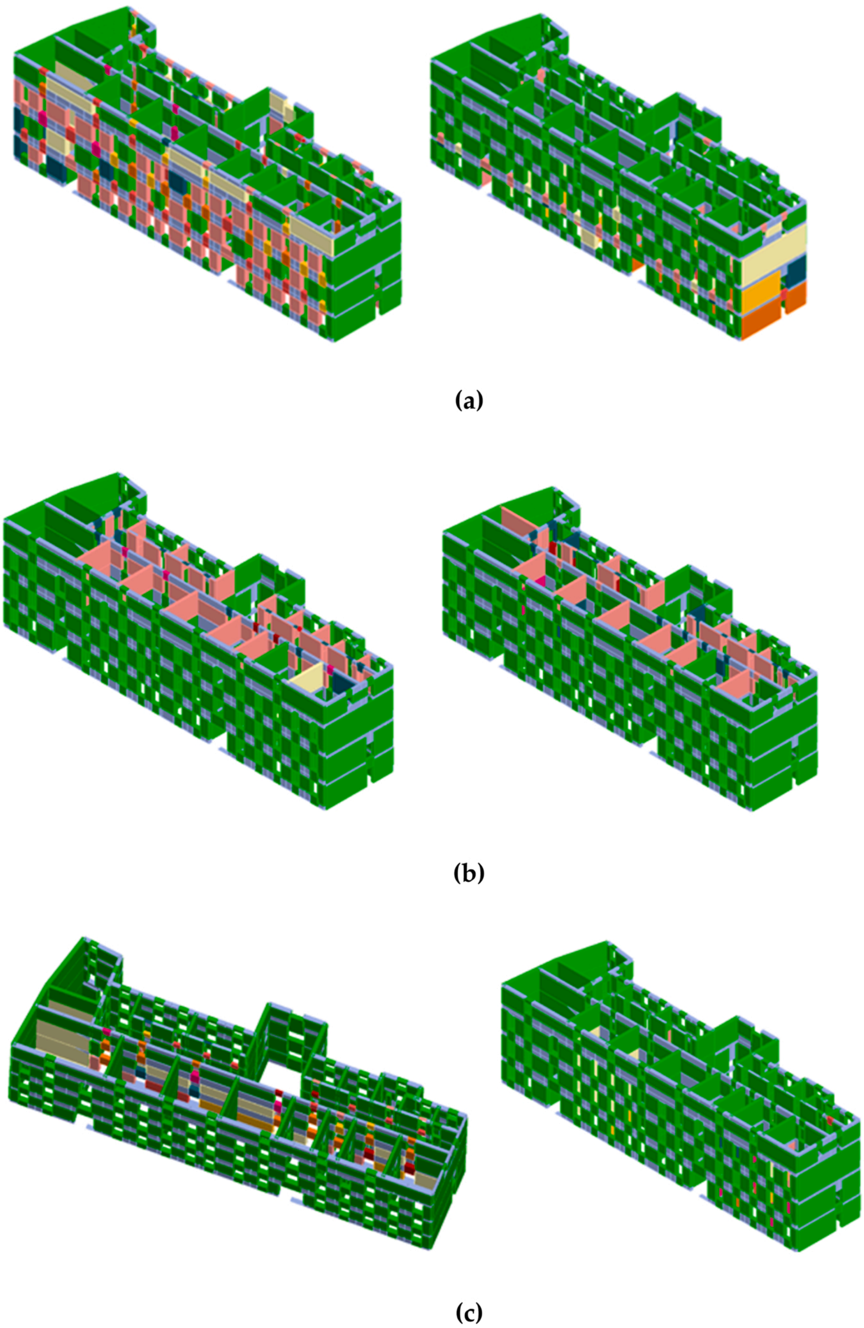


Fig. 16. Damage visualization for the most critical analysis in x (left) and y direction (right) (a) model strengthened by the FRCM system (b) model strengthened by shotcrete (c) model strengthened by FRCM systems and shotcrete.

casualties and psychological consequences for society. Poor design and construction, degraded material, and other factors resulted in important damage from the earthquake that hit Croatia in 2020.

The inspections determined that newly designed structures (mostly reinforced concrete structures) remained undamaged, while the greatest damage was observed on the masonry structures. Structural renovation of Zagreb has begun, and the city has turned into a construction site. A large number of damaged buildings, labor shortage, high renovation costs and other difficulties affect the quality of structural renovation. Many engineers use traditional strengthening techniques (which mainly include reinforced concrete) as they have more experience with them. The main flaw of traditional strengthening methods is their invasiveness. Since many damaged buildings have the status of cultural heritage, invasive strengthening methods are jeopardizing the cultural identity of building. The aim of this paper is to bring engineers closer to the use of unconventional strengthening methods. Regarding the presented case study,

Table 9
Calculation of renovation costs – FRCM system [43].

Work task	Unit of measure	Unit price (€)	Amount	Total price (€)
Operating mobile scaffolding to perform the required work	m^2	15,85	3.523,65	55.849,86
Complete removal of plaster from the walls (up to clean brick)	m^2	4,65	9.657,60	44.907,84
Collecting waste	m^2	2,00	9.657,60	19.315,20
Loading and removal of waste to the landfill	m^3	46,25	434,59	20.099,79
Re-grouting joints with mortar	m^2	13,25	2.917,70	38.659,53
Setting up an FRCM system	m^2	33,05	9.657,60	319.183,68
Applying new plaster	m^2	10,60	9.657,60	102.370,56
Total	–	–	–	600.386,46
Total	m^2			219,76

Table 10
Calculation of renovation costs – shotcrete.

Work task	Unit of measure	Unit price (€)	Amount	Total price (€)
Operating mobile scaffolding to perform the required work	m^2	15,85	1.075,08	17.040,02
Complete removal of plaster from the walls (up to clean brick)	m^2	4,65	5.875,80	27.322,47
Collecting waste	m^2	2,00	5.875,80	11.751,60
Loading and removal of waste to the landfill	m^3	46,25	264,41	12.228,96
Installation of anchors for placing reinforcing mesh on load-bearing walls (4 pcs / m^2)	pcs	2,65	23.504,00	62.285,60
Installation of Q503 reinforcement mesh on walls	kg	1,35	47.182,67	63.696,60
Installation of shotcrete	m^3	112,30	352,55	39.591,37
Applying new plaster	m^2	10,60	5.875,80	62.283,48
Total	–	–	–	296.100,10
Total	m^2			108,38

Table 11
Calculation of renovation costs – FRCM system and shotcrete.

Work description	Unit of measure	Unit price (€)	Amount	Total price (€)
Operating mobile scaffolding to perform the required work	m^2	15,85	1.075,08	17.040,02
Complete removal of plaster from the walls (up to clean brick)	m^2	4,65	7.670,40	35.667,36
Collecting waste	m^2	2,00	7.670,40	15.340,80
Loading and removal of waste to the landfill	m^3	46,25	345,17	15.964,11
Re-grouting joints with mortar	m^2	13,25	1.458,85	19.329,76
Setting up an FRCM system	m^2	33,05	4.828,80	159.591,84
Installation of anchors for installing reinforcing mesh on load-bearing walls (4 pcs / m^2)	pcs	2,65	11.367,00	30.122,55
Installation of Q503 reinforcement mesh on walls	kg	1,35	22.818,05	30.804,37
Installation of shotcrete	m^3	112,30	170,50	19.147,15
Applying new plaster	m^2	10,60	7.670,40	81.306,24
Total	–	–	–	424.314,20
Total	m^2			155,31

the authors of this manuscript participated in the process of detailed post-earthquake assessment and defining of structural performance. According to the 1st version of the new Law on Reconstruction by Earthquake-Damaged Buildings in the City of Zagreb, Krapina-Zagorje County and Zagreb County [10], the engineers who were obtaining this 1st stage (assessment and structural performance) were supposed to do the strengthening project. It was a mandatory rule. However, several months later, the law changed due to numerous implementation problems. According to the new version of the law, the public tender was announced and, other designers were chosen to do the strengthening project. The building will be strengthened by concrete shotcreting and by adding several new concrete walls.

In this manuscript, three variants of strengthening are modeled and compared in terms of costs and achieved earthquake resistance. Structural models were subjected to monotonically increasing horizontal loads until the limit states were reached. For newly designed structures, relevant codes define limit states according to return periods of 95 and 475 years. Since those requirements are hard to meet for existing structures, Croatian state passed a law which defined different renovation levels. In addition to limit states for 95 (level 2) and 475 (level 4) years, an additional limit state with return period of 225 (level 3) years was defined. The goal of this paper was to strengthen the structure to level 3. Results have shown that the structure strengthened by shotcrete was subjected to acceleration 21% higher than the one defined by relevant codes, and the structure would still fulfill the limited damage requirements. Compliance with the case can be reached for a model strengthened with FRCM only and a combination of shotcrete and FRCM. Although the lowest costs and highest capacity refer to strengthening by shotcrete, its invasiveness must not be neglected especially in case of buildings with cultural heritage status (the seismic renovation of the Rector's Palace in Dubrovnik after the earthquake in 1979 caused a loss of

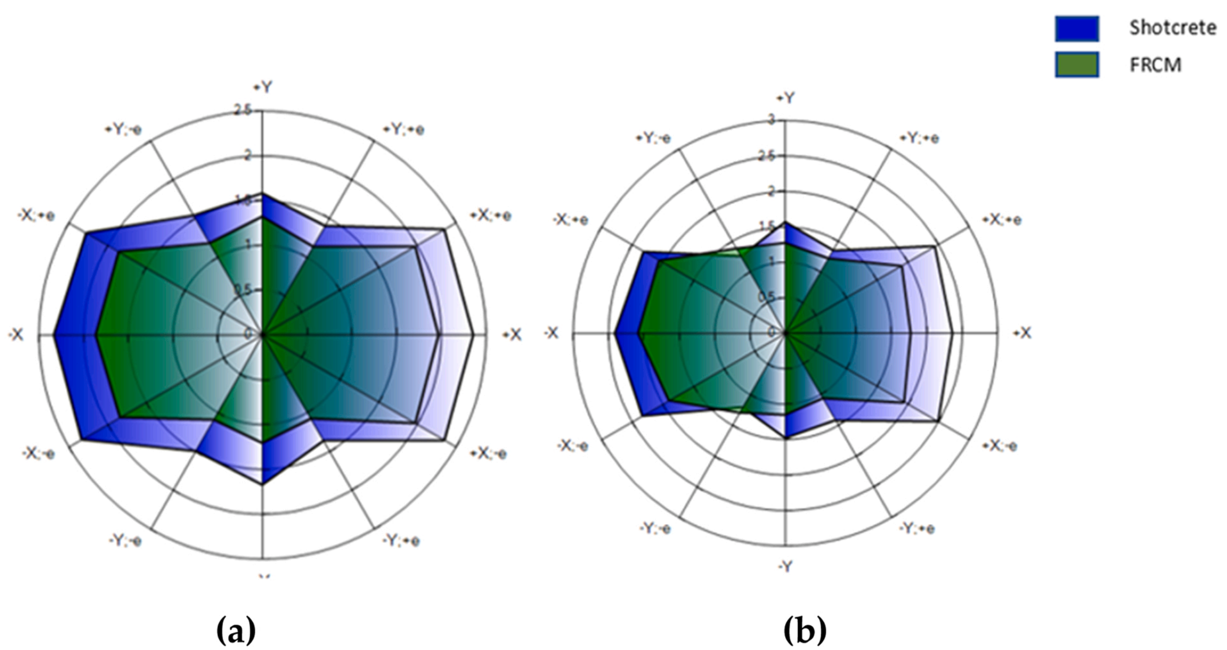


Fig. 17. Comparison of risk indices of models strengthened by FRCM and model strengthened by shotcrete (a) uniform load distribution; (b) modal load distribution.

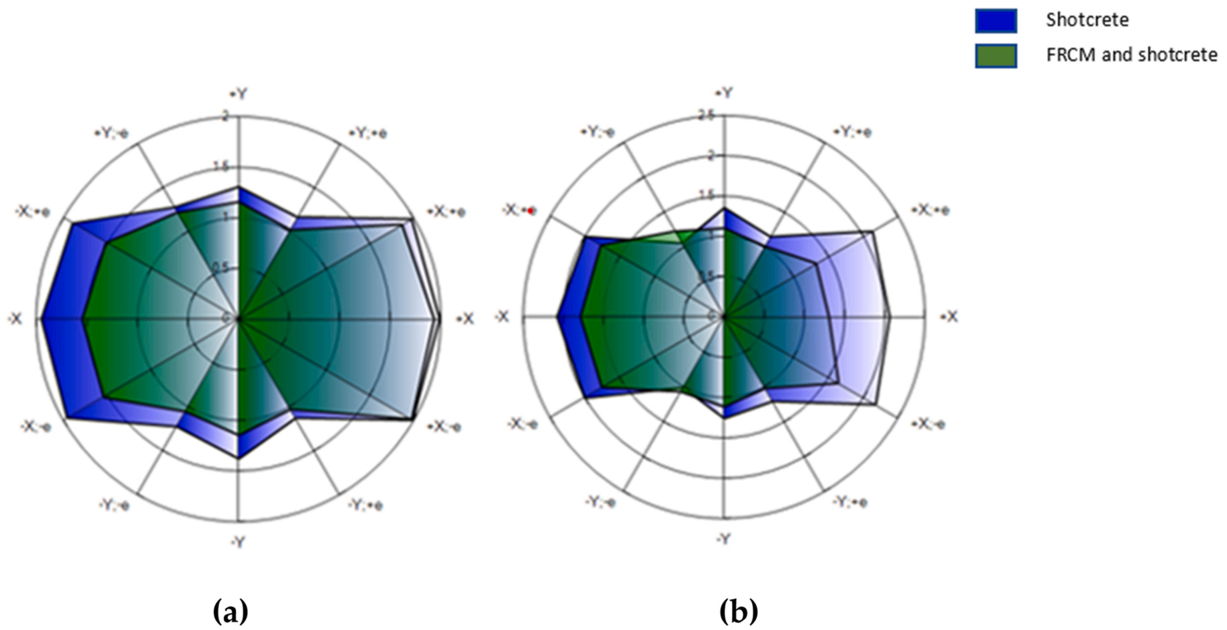


Fig. 18. Comparison of risk indices of model strengthened by FRCM and model strengthened by combination of shotcrete and FRCM (a) uniform load distribution; (b) modal load distribution.

inestimable value [46]). Furthermore, the construction sector tends to follow the sustainability trends. Considering the climate change impact only, the shotcrete application causes 3,65 higher carbon dioxide emission than FRCM system. Given the carbon cost is expected to increase extensively and due to the global policy of reduction of the CO_2 emission, application of natural fibers may represent a competitive solution.

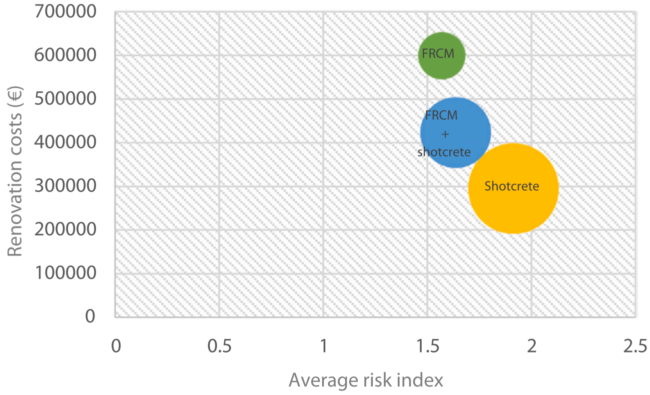


Fig. 19. Renovation costs, average risk indices and environmental impact.

Table 12
Calculation CO_2 emission.

	Unit measure	CO2 emission (kg)	Amount	Total CO_2 emission (kg)
FRCM				
Fibers	kg	3,91	2.748,00	10.744,68
Concrete	m^3	282,00	154,17	43.475,94
Σ				54.220,62
Shotcrete				
Concrete	m^3	282,00	416,41	117.427,62
Steel	kg	5,01	41.798,15	209.408,73
Σ				326.836,35
FRCM + Shotcrete				
Fibers	kg	3,91	482,51	1.886,61
Concrete	m^3	282,00	292,47	82.476,54
Steel	kg	5,01	22.728,85	113.871,54
Σ				198.234,69

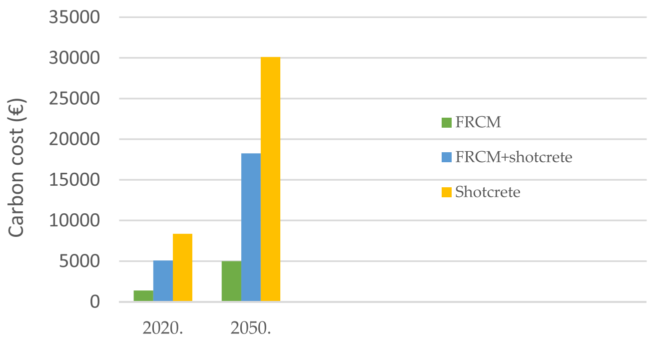


Fig. 20. Carbon costs for current market and future projections.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mislav Stepinac reports financial support was provided by Croatian Science Foundation.

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