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IMPROVEMENT OF BUILDING'S WALLS BEARING CAPACITY AFTER AN EARTHQUAKE

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Abstract

Strengthening and increasing the capacity of load-bearing walls of buildings after an earthquake is a challenge that requires special study. A viable option is strengthening using standard cement-based materials.

This paper will first present and discuss the buildings with load-bearing walls that have shown earthquake survival ability, as well as some methods to improve their performance.

The example that is used for discussion is a building that has suffered significant damage from the 2019 earthquake in Albania. The paper will present the calculation of the performance and load-carrying capacity of this building with the load-bearing walls made of clay and silicate bricks after an earthquake of magnitude M=6.2 Richter. The building comprises load-bearing walls and was built in the 1960s-70s. The materials characteristics used in calculations are derived from laboratory tests and on-site non-destructive testing. The results obtained from the calculation of the building before and after the earthquake and after the reinforcing of the building will be compared. The strengthening of walls is made using cement-based materials. The calculations are performed using SAP2000 and ETABS software and include static and dynamic performance.

The results of the calculations will be analyzed to conclude the effectiveness of the rehabilitation of the buildings. The environmental and socio-economic impacts on society from the strengthening of buildings damaged by earthquakes will also be presented.

Keywords: earthquake, buildings, damage, strengthening, materials, impact.

1. Introduction

Early constructions in most cases are made of load-bearing walls with clay, silicate or stone bricks. Masonry is one of the oldest types of construction. The building material brick was easy to produce [1]. Taking into account structural-physical properties and the quite easy construction process, this construction system is used until today. This paper will present the results obtained from the software calculations of the building that survived the M=6.3 earthquake in Albania in 2019. Earthquakes are often accompanied by aftershocks which may cause additional damage to an already damaged structure or lead to failure [1]. The reason to analyse the building which suffered damage – vertical and diagonal cracks in the walls, is to identify the possibility of its survival and use after the earthquake. During the treatments, samples were taken and the walls were tested with destructive methods. The paper presents dimensions, the static system and linear and non-linear analysis of the building. During the analysis, the reduction of mass is taken into account by eliminating heavy layers, heavy non-constructive walls and replacing them with lighter material. Reductions in mass result in direct reductions in both the forces and deformations produced by earthquakes and therefore can be used in lieu of structural strengthening and stiffening [2]. From the obtained results, the dynamic characteristics of the building and the bearing capacity were calculated. The building was built from load-bearing walls in the years 1960-70. All the findings are presented in tabular form. Pre-earthquake performance was analyzed using the laboratory results, while the post-earthquake performance analysis took into account reducing the bearing capacity of the cracked walls based on the codes and technical norms for this type of objects such as FEMA 273, EC6 & EC8. The analysis was also made for the case of rehabilitation and improvement of building performance. Its rehabilitation is made with ordinary cement-based material. The strengthening is executed in two layers of 25 mm on each side of the wall. Then the performance

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and bearing capacity of the building was calculated using the linear and nonlinear calculations of the ETABS and SAP2000 software. During the calculations, the dynamic and static parameters were taken as a basis spectrum data for the area of Tirana where the facility is built. The results obtained in the three cases are analyzed and important conclusions are drawn. From the performance calculations, a great stiffness of the building can be seen. With the addition of mesh reinforcement, the ductility of the building increases. In such cases, the results can be of great benefit for executing rehabilitation at an optimal cost. Rehabilitation and reinforcement from standard materials also has a socio-economic impact. The investment will be returned in a shorter time than the cost of expensive modern materials. The purpose of the reinforcement is sufficiently achieved and the building will survive the challenges in the future and meet the demands of the community. It also has an important impact on the environment. The renovation preserves the green space and the pollution from the demolition of the entire building. A total demolition would have a high cost and environmental pollution from waste. Such treatment would emit a significant amount of carbon dioxide.

2. Geometric and mechanical characteristics of the building

The geometric and mechanical characteristics of the building members and materials are presented in the following sections. This includes a description of the old and new design and the materials that have been used and have an impact on the structure and its behaviour to seismic impacts.

2.1 Geometric characteristics

The building was built in 1966 and serves as a hospital in Tirana. The foundations are made of stone and are unreinforced with different dimensions for balancing the stresses and the depth of the foundation is hf=1.30m. The soil has a good bearing capacity σ=0.25 MPa. The walls can be classified as primary, secondary and dividing or tertiary walls: primary walls are the bearing walls which also carry external loads and are longitudinal with thicknesses t_1=50 cm, t_2=40 cm, t_3=30 cm, secondary walls are most of the transverse walls that have a thickness of t_1=30 cm and t_2=25 cm, while the dividing walls, that have the purpose of dividing spaces only and can be removed and replaced with lighter walls, are t_1=20 and t_2=12 cm. The floor structure or floor slab system is made of clay elements filled with concrete in a patterned shape every 20 cm and ribs t=8 cm, plate thickness d=4 cm. There are beams on the walls from a C-16/20 concrete grade along the building's perimeter and the columns inside the building, in the elevator and installation space, dimensions w/h = 40/40 cm, w/h=40/25 cm and w/h =25/25 cm. The loads from the floor layers and internal walls are g=3.70 kN/m^2 on the floors and g=3.50 kN/m^2 on the roof.

2.1.1 Design of old existing building

The plan view of the old existing building is shown in Fig. 1, while Figs. 2 and 3 show some photos of damage after the earthquake, prior to and after the mortar layer was removed. Before removing the mortar, vertical cracks, tending diagonally, can be seen, and they were temporarily closed until the building was completely repaired. After the mortar was removed, diagonal cracks can be seen.

2.1.2 Renovation design of the building

During the renovation, it was taken as a basis that the materials that will be used in the floor and the tertiary or dividing walls should have a lighter specific weight. Partition walls are taken from Knauf walls, and now we have a floor load reduction of g=2.80 kN/m^2 on floors and of g=1.50 kN/m^2 on the roof. The other walls were not damaged, they were only reinforced with two layers of compressed or cast plaster with a thickness of t=25 mm, class C-25/30. Fig. 4 shows the renovation design plans with the walls' changes. Fig. 5 illustrates the renovation execution of the building which is the subject of the analysis.

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a)

b)

Figure 1. Design of the old building: a) Basement story, ground story; b) First story, second story.

Figure 2. Cracks in the wall from the earthquake in 2019 Tirana, Albania.

Figure 3. Wall after demolishing mortar.

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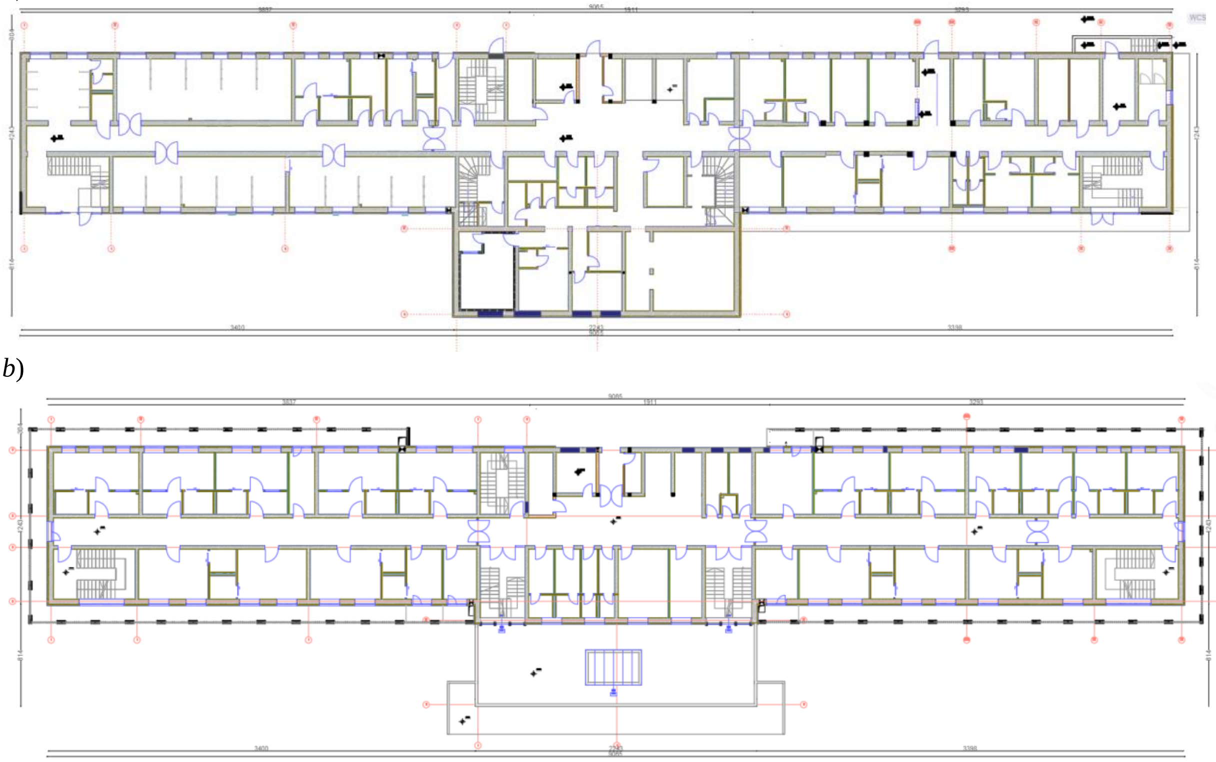

Figure 4. Design of renovated building: a) Basement story, ground story; b) First story, second story.

Figure 5. Renovated building.

2.2 Mechanical characteristics

The mechanical characteristics of materials used in the existing building are given in Table 1. These characteristics are derived from testing results. Concrete tested by destructive methods and taking samples on-site turns out to be class C-20/25, and the steel used is class S 240/360. The samples were taken and the results were obtained for the silicate and clay bricks, the paste for plastering, and the type of the wall masonry and its mechanical characteristics according to the technical norms (e.g. EN 772)

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were also obtained. The characteristics of materials composing the structure are input data for structural analysis. Namely, the compressive-tensile strength of the materials, their modulus of elasticity and their Poisson ratio are of primary importance [3].

Table 1 – Mechanical characteristics of materials in MPa

Materials	**f_{ck} (MPa)**	**f_b (MPa)**	**f_m (MPa)**	**f_k (MPa)**	**f_{yk} (MPa)**	**E (MPa)**	**G (MPa)**
C-20/25	20					30 000	12 000
S-240/360					240	200 000	80 000
Silicate Brick		20.6				20 600	8 240
Clay Brick		13.67				13 670	5 468
Mortar			7			7 000	2 800
Masonry clay				6.15		6 150	2 460
Masonry silicate				8.37		8 370	3 348
C-25/30-Cement mortar	25					31 000	12 400
S-400/500-steel mesh					400	200 000	80 000

The calculation of the characteristic value of the masonry using the characteristic values for brick and mortar is taken from EC6, the characteristic compressive strength of masonry should be determined from [4]:

$$f_k = K\, f_b^{\alpha}\, f_m^{\beta} \tag{1}$$

f_k – characteristic compression strength of masonry

K – is constant from tab.3.3 page 37, EC 6-1-1 2006 [3]

α, β – are constants

f_b – normalised mean compressive strength of units

f_m – is the compressive strength of mortar.

3. Results of Case Analysis

To calculate the performance and bearing capacity of the building, linear and non-linear analyses were used. In the analysis, the permanent live loads were applied. The modal and seismic analysis was based on the seismic conditions of Tirana, from the data extracted after the 2019 earthquake. The acceleration was obtained a_g=0.29g, the object of importance γ_I=1.40, while the soil is of category C and the behaviour factor is q=2.50 for buildings with unreinforced retaining walls according to EC8 [5]. Table 2 presents the loads before and after renovation.

Table 2 – Comparison of loads on the building

	Building before renovation	**Building after renovation**	**Comparison (%)**
Dead Load of Layer in floor	3.70 kN/m2	2.80 kN/m2	-24.30
Live Load in Floor	5.0 kN/m2	5.0 kN/m2	0.00
Dead Load of Layer in roof	3.50 kN/m2	1.50 kN/m2	-57.14
Seismic acceleration a_g	0.24 g	0.29 g	20.83

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3.1 Linear analysis

The linear analysis of the building was carried out based on the data extracted and presented in Tables 1 and 2. Table 3 summarizes the dynamic data of the building and the participation of the mass in vibration modes. Four cases were analyzed by changing the construction and loading conditions in this analysis. Practically most of the structural and non-structural damage sustained in such buildings is produced by lateral displacements [7]. Therefore, the focus of calculations and design of the buildings is to eliminate as much as possible lateral displacements. Table 3 shows the results for the first three periods for each case.

Table 3 – Periods and mass participation

Building	Modes	Periods (s)	Mx	My	MRz
Old Building before the earthquake	1	0.214	0	0.721	0.007
	2	0.172	0.001	0.005	0.741
	3	0.083	0.736	0	0.741
Old Building after the earthquake	1	0.237	0	0.651	0.025
	2	0.21	0.02	0.02	0.68
	3	0.108	0.664	0	0.68
Renovated Building with cement mortar	1	0.208	0	0.677	0.01
	2	0.171	0	0.008	0.7
	3	0.086	0.71	0	0.7
Renovated Building with cement mortar and reinforced mesh	1	0.215	0	0.687	0.009
	2	0.174	0	0.007	0.71
	3	0.088	0.719	0	0.71

In Fig. 6, the cases after the earthquake are presented as follows: the type of cracks encountered; the form of repair with cement mortar t=25 mm with casting; and repair using the grid Ø 3/100/100 mm reinforcement, each with connecting anchors (5 pieces in m^2 of cement mortar t=25 mm).

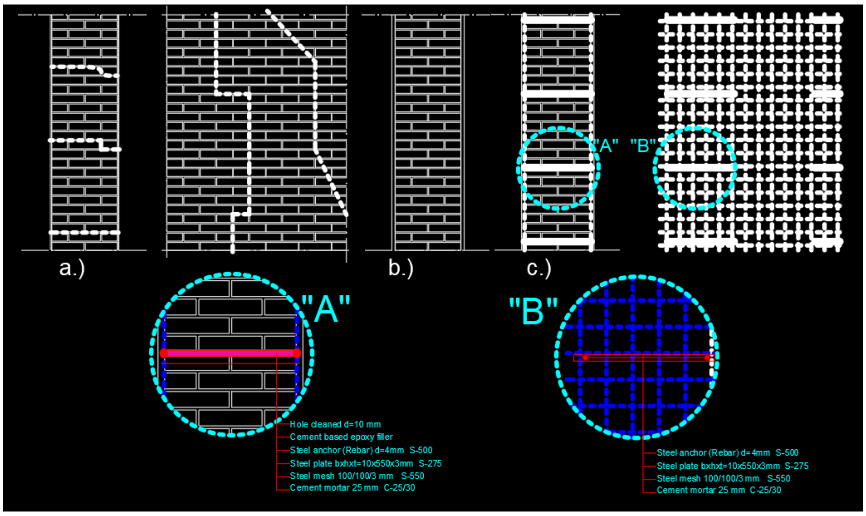

Figure 6. a) Cracked wall after the earthquake; b) Repaired wall; c) Proposed reinforced wall.

Center of mass and centre of rigidity were calculated using ETABS 19 software. Their values are listed in Table 4 along with the eccentricity in both orthogonal directions x and y for each story.

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Table 4 – Centre of rigidity and centre of mass for each story, and each of the cases considered – before the earthquake, after the earthquake, renovated with mortar only, and renovated with added reinforcement (XCCM, YCCM, XCR, YCR and ex, ey)

	Story	XCCM (m)	YCCM (m)	XCR (m)	YCR (m)	ex (m)	ey (m)
Building before earthquake	1	44.971	13.330	47.135	13.048	2.164	0.282
	2	45.109	13.488	46.307	12.663	1.198	0.825
	3	45.128	14.027	46.163	13.021	1.035	1.006
	4	45.064	14.046	46.172	13.258	1.108	0.788
Building after earthquake	1	44.011	13.293	47.370	12.820	3.3591	0.473
	2	45.028	13.552	46.377	12.453	1.3492	1.099
	3	45.042	14.327	46.162	12.877	1.1192	1.450
	4	44.976	14.156	46.118	13.171	1.1413	0.985
Renovated building with cement mortar 25 mm	1	44.288	13.351	46.523	13.577	2.235	0.226
	2	45.312	13.442	46.143	13.430	0.832	0.012
	3	45.284	14.224	46.326	13.576	1.042	0.648
	4	45.073	14.063	46.463	13.666	1.390	0.397
Renovated building with cement mortar 25 mm and steel mesh	1	44.327	13.362	46.581	13.580	2.254	0.219
	2	45.306	13.451	46.186	13.428	0.880	0.023
	3	45.270	14.225	46.346	13.577	1.076	0.648
	4	45.063	14.069	46.477	13.662	1.414	0.408

Repairing walls using layers of cement plaster and metal mesh as reinforcing elements also changes the performance of the wall out of its plane. This type of wall cross-section works like composite elements. The mesh on the surface absorbs the tensile stress caused by the seismic impacts on the wall.

3.2 Nonlinear analysis

Non-linear analysis was also done for all cases. By adopting pushover analysis as a nonlinear analysis tool, the behaviour of damaged buildings may be simulated with suitable modification of plastic hinges for damaged elements. Such modification is based on stiffness, strength, and displacement reduction factors accounting for the achieved damage states for the structural elements, as could be detected by visual inspection of post-earthquake damage [8]. Therefore, the results show that we are dealing with a heavy object. The failure mechanism did not depend on the materials of construction but depended on structural configuration [6]. The configuration of the static system and the design of the bearing walls of the buildings have a major role in the collapse of buildings from the action of seismic loads. The representation of the displacement of the building in the direction of the y-axis by the action of the force is shown in Fig. 7, indicating performance for each of the cases.

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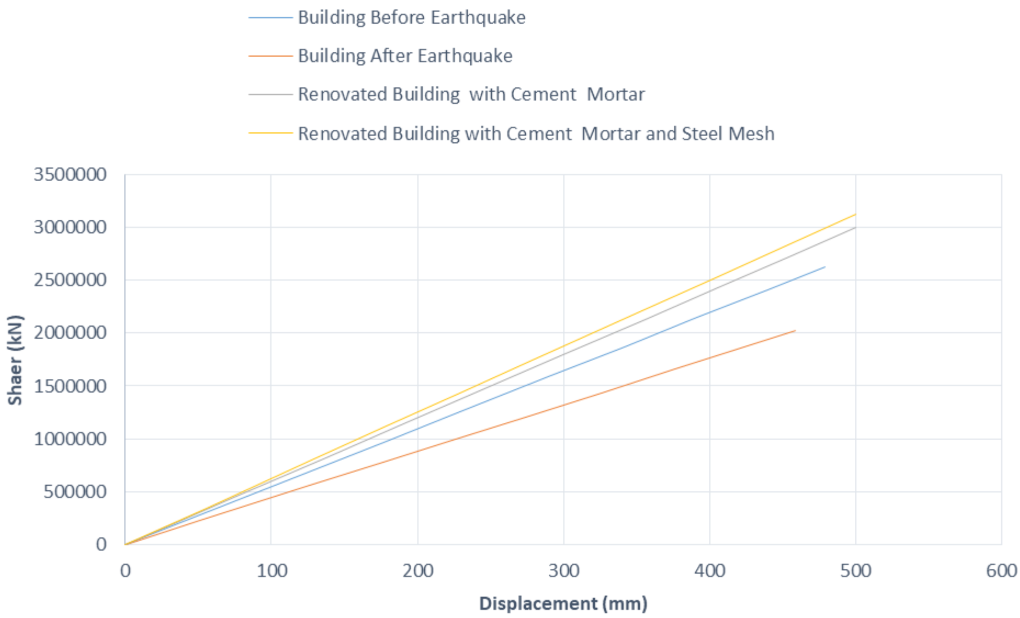

Figure 7. Pushover Curve – Base Shear vs Displacement for all cases.

Table 5 shows the comparison of the force for a base displacement by turning it into a percentage for each analysed case. From EC8 the designed displacement is:

$$d_g = 0.025 \cdot a_g \cdot S \cdot T_C \cdot T_D \quad (2)$$

$$a_g = \gamma_I \cdot a_{gR} \quad (3)$$

Therefore, the comparison is made for the following value of the designed displacement:

$d_g = 0.025 \cdot 0{,}354 \cdot g \cdot 1{,}15 \cdot 0{,}6 \cdot 2{,}0 = 119{,}81$ mm

Table 5 – Comparison of results in percentage

Cases	d_g **(mm)**	**Shear Force (kN)**	**Comparison with the building before the earthquake (%)**	**Comparison with the building after the earthquake (%)**
Building before the earthquake	119.81	656 436.14	0	24.276
Building after the earthquake	119.81	528 210.152	-19.534	0
Renovated building with cement mortar 25 mm	119.81	718 618.65	9.473	36.048
Renovated building with cement mortar 25 mm and steel mesh	119.81	749 484.071	14.175	41.891

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Pushover capacity curves in y direction, from ETABS and according to EC8, are shown in Fig. 8 for four considered cases. Y-direction is presented because stiffness is lower in that direction than in x direction, and most major damage during the earthquake in Tirana, Albania came from the earthquake action in y direction. Comparison of capacity in percentage at the target displacement in y direction is provided in Table 6. Target displacement is read from ETABS 19, and is according to EC8 2004. Shear forces and performance percentages are calculated for the target displacement.

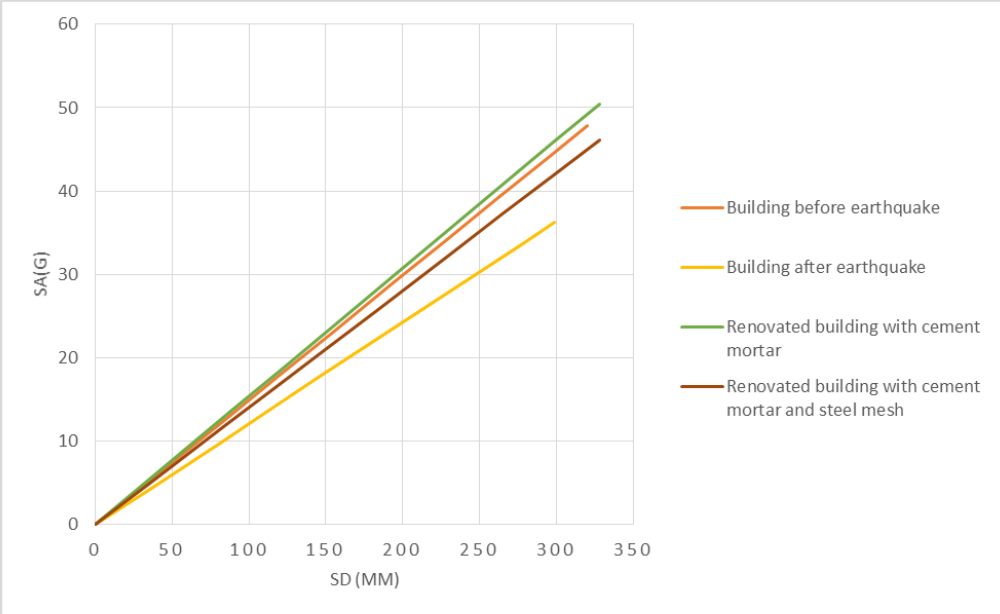

Figure 8. Pushover capacity curve SD-spectral displacement vs SA-spectral acceleration as EC8 2004.

Table 6 – Comparison of case capacities in percentage according to EC8 2004, d_t – target displacement

Cases	**d_t (mm)**	**Shear Force (kN)**	**Comparison (%)**
Old building before the Earthquake	3.826	20 979.225	0
Old building after the Earthquake	4.989	22 017.828	-25.447
Renovated building with cement mortar 25 mm	3.772	22 638.734	9.322
Renovated building with cement mortar 25 mm and steel mesh	4.189	26 216.363	15.476

4. Discussion of the results

The results from the linear and non-linear approaches are discussed in this chapter. The loads that were used in the renovated building are lighter than those that were in the building before the earthquake. Comparatively, for the floors (as presented in Table 2), it can be seen that there is a 24.30% decrease, while for the roof the load is 57.14% lighter. The seismic load for calculation for the return period of 10% in 475 years has increased from 0.24g to 0.29g, after the 2019 earthquake in Durres, Albania, which is an increase of 20.83%. The calculations were carried using these values. The results show an impressively positive effect of interventions considered – every variant leads to better performance than the one before the earthquake. The building has high stiffness, which is also demonstrated by the periods obtained from the linear analysis. There is a large eccentricity in the direction of the x-axis, which in the results is reflected by twisting in the direction of the translatory oscillations x and y. Because of this, the second period appears as the angular period. The periods and the centre of mass and stiffness are presented in Tables 3 and 4. The results from the non-linear analysis using pushover analysis were

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shown in Tables 5 and 6. Fig. 7 presents the comparison of the displacement curves and the shear force of the building. It can be seen from those results that the building has the best performance in the case of renovation which is made with two layers of plaster with cement mortar and metal mesh 3/100/100 mm. For comparison, the displacement of a point d_g=119.81 mm was calculated according to EC8 (Table 5). To achieve this displacement, the necessary force was calculated, and performance was compared to that of the building before the earthquake. After the earthquake, the building loses in load-carrying capacity and stability by about 19.534%, while after renovation using the standard material plaster with 25 mm cement mortar, the building shows a better performance than the building before the earthquake by 9.473%. If the plastering of the walls is done with cement mortar, but we also add the metal mesh 3/100/100 mm and anchor with 5 anchors per square meter according to Fig. 6. c, then the performance in bearing capacity of the building increases compared to that before the earthquake by 14.175%. These comparisons were made using the method of displacement and shear force in pushover in the direction of the y-axis because, in the direction of the x-axis, we have great inertia and the displacements are negligible. Fig. 8 shows the diagrams of the four cases using the diagrams of the capacity curves according to EC8 2004 using the displacement and the shear force and setting the target displacement. Table 6 presents the results for the target displacement, which force it can withstand and the capacity is extracted in percentage, again in comparison to the building before the earthquake. From the results presented, the building after the earthquake loses capacity by about 25.447%, while after interventions with the plastering of the walls with 25 mm thick cement varnish on both sides of the walls, the capacity increased by 9.322%. If the steel mesh 3/100/100 mm is also used in the building, then the capacity of the building compared to the building before the earthquake increases by 15.476%.

It can be seen that the intervention results are impressive and it is possible to achieve a lot in the socio-economic aspect and in the preservation of the environment and the emission of carbon dioxide, as discussed earlier.

5. Conclusion

From the obtained and analyzed results, we conclude that by reducing the specific weight of the layers of materials used, they positively affect the response of the building by reducing the impact force from the earthquake. Lightening the weight of the materials and reducing the impact force from the earthquake enables smaller-scale damage to buildings. From the results obtained with the use of plaster reinforcement with a cement base and mesh reinforcement, good performance of the building may be observed, especially when it is known that the acceleration a_g has also increased.

The results show that the buildings that were repaired with cement mortar on both sides of the wall with 25 mm increased the performance (1.1-9.3) % from the performance of the building before the earthquake, depending on which method is evaluated.

The results obtained for the walls repaired with 25 mm cement mortar and reinforced with 3/100/100 mm steel mesh anchored on both sides of the wall increase the performance of the building (3.8-15.4)% from the building before the earthquake.

With the restructuring of the internal tertiary walls, which were made of clay bricks and their replacement with modern light walls such as canvas, also affect the reduction of eccentricity and improve the behaviour of the building against the earthquake, which reduces the rotational strength of the building and reduces the damage.

The use of steel mesh increases the ductility of the walls and eliminates cracks from earthquakes on the surface of the walls and increases the stability of the wall outside its plane.

After an earthquake, quick intervention is always required, and the use of standard materials is an ideal solution. Whereby using the plastering of the walls with cement plaster cast to create great compactness, not only the sturdiness and the initial capacity of the building obtained but also the absorption capacity of the earthquake is increased. But one of the benefits is how quickly remediation can be made and the building put into use, reducing the financial costs of remediation and rent for residents who need to be sheltered after the earthquake. The impact on the environment is evident

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because the pollution from the collapse of the building is eliminated, the cost of waste treatment is eliminated, and with it the emission of carbon dioxide and gases that affect global warming.

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