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BASE ISOLATION OF AN EXISTING REINFORCED CONCRETE BUILDING

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Abstract

Croatia is located in a seismically active area where moderate to strong earthquakes occur regularly. In addition, the building stock is relatively old and not maintained, so the seismic risk is high. This is evidenced by the damage caused by the earthquakes in Zagreb and Petrinja in 2020. Currently, the reconstruction of earthquake-damaged buildings is mainly carried out using standard structural strengthening methods. However, the application of base isolation has significant potential and could be an effective solution for a specific type of building.

In Croatia, base isolation has not yet been used to increase the seismic safety of buildings. This paper investigates the possibility of applying base isolation system on the existing reinforced concrete frame building from the 1930s. In the paper, the building retrofitting solution with base isolation is compared with the conventional strengthening solution.

The application of base isolation in existing buildings was described and linear and non-linear analyses were carried out using the ETABS software package. Based on results, the construction costs were analyzed and compared. The results show the potential of base isolation as an effective solution for the reconstruction of existing buildings.

Keywords: earthquake, frame structure, numerical model, ETABS, base isolation

1. Introduction

Complex reconstruction works with significant material damage in the area of Zagreb and Sisak-Moslavina County are being carried out on an older building stock that mostly consists of masonry buildings and reinforced concrete frame structures designed before the first seismic codes were used in Croatia. [1]

The ongoing process of reconstruction and strengthening of a large number of buildings still requires a significant amount of financial resources. In order to carry out complex interventions on the structure, it is usually necessary to remove all floor and wall coverings, so relocation and finding a suitable replacement location are necessary. All of the activities above add additional financial costs and make the decision of the reconstruction more difficult. The issue of relocation is particularly prominent in public buildings, and there is a need to increase the building's resistance to seismic action to a sufficient level, if possible without relocation, and to maintain the building in full or partial function during the work.

Public buildings in the Zagreb area were mostly built in the mid-20th century, when reinforced concrete was increasingly used in construction. The structures are constructed as frames, with larger spans and slimmer elements, with ribbed and fine-ribbed ceilings, but without the necessary knowledge of earthquake-resistant construction and adequate seismic design. The biggest initial deficiency due to which buildings do not have sufficient earthquake resistance is lack of adequate details and insufficient resistance of sections to achieve seismic safety, as well as insufficient ductility of reinforced concrete element joints.[2]

In this paper, using the example of an existing public reinforced concrete frame structure, that already implemented retrofitting using the conventional method of inserting walls is compared with a consideration of the alternative option of applying base isolation. Building was renovated in the process of reconstruction after the earthquake using the conventional retrofitting method, which necessitated

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complete relocation and additional financial costs. This paper will present a description of the building, investigative works, parameters and a model of the existing state of the structure, as well as a reconstruction using a base isolation. The results obtained and the necessary interventions were compared with the already implemented reconstruction using conventional methods, and a financial comparison of the solutions used was also made.

2. General Description of Structure

The structure considered in this paper is located in Zagreb and is part of the Faculty of Agriculture complex, called "Pavilion 1", and belongs to the category of public buildings. [3] The building is a reinforced concrete frame structure from the 1930s, built at a time when there were no technical regulations for the design and calculation of structures for earthquakes.

The building's floor plan dimensions are 40.50 x 16.00 m, mostly in rectangular shape, with an annex on the north side measuring 10.50 x 6.50 m. The building consists of a ground floor, first floor, second floor and attic, and the height of the building from the ground level is approximately 17.00 m. In Fig. 1 building is shown before retrofit.

Figure 1. a) South side; b) Main entrance [3]

As part of the available documentation of the building, archival drawings were used, according to which the building was designed in 1932. The original load-bearing structure consists of a system of connected reinforced concrete columns and beams that form transverse frames, while in the longitudinal direction the frames are formed only in the planes of the facades, as shown in Fig. 2. According to the analysis of the archival drawings, it is assumed that the transverse beams were constructed in the main axes at the point of support of the columns (at a distance of 5 meters), at the height of the ribbed ceiling. The column grid is at a distance of 5 meters, the dimensions of the internal columns are variable and decrease in height. The dimensions of the load-bearing elements and the characteristics of the material were determined by investigative works as part of the reconstruction project [3].

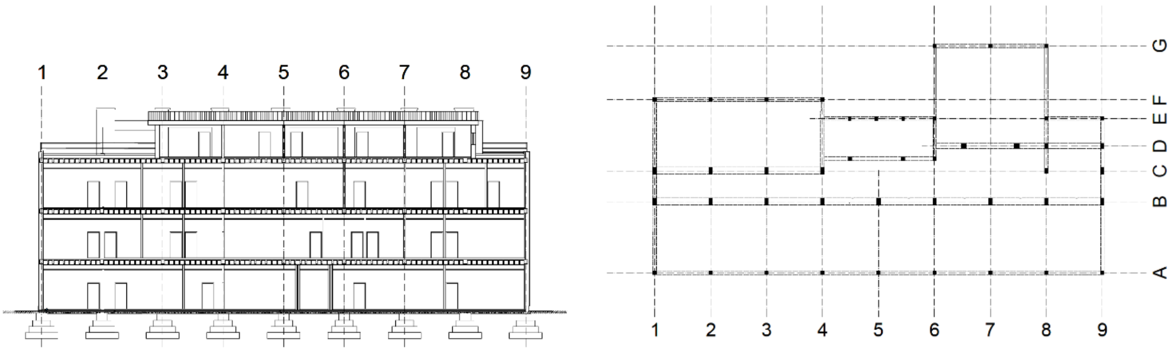

Figure 2. Building plans a) Elevation; b) Floor plan

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According to investigation works [4], the ceiling structure is supported in the transverse direction on longitudinal beams. In the central part of the building there is a reinforced concrete staircase. The foundations of structure are isolated. The inter-story ceiling structure is reinforced concrete, the so-called ribbed ceiling, and the ribs are connected to a 5 cm thick concrete slab. On the underside of the ribs, wooden battens, are installed, on which plaster is applied.

Some of the archival drawings have been preserved, but there is no data about mechanical properties of the used materials. As part of the reconstruction project, investigative work was carried out. According to the Structural investigation report of the structural testing laboratory of the Faculty of Civil Engineering [4], the shear strength of the masonry, the dimensions of the structural elements, as well as the quality of the material were determined. Concrete samples were taken by roller drilling and compressive strength testing of reinforced concrete columns was investigated on the ground floor and upper floors of the building, and non-destructive sclerometer testing was used to assess the quality of the concrete. Fig. 3 shows the reinforcement of the 30/30 cm column.

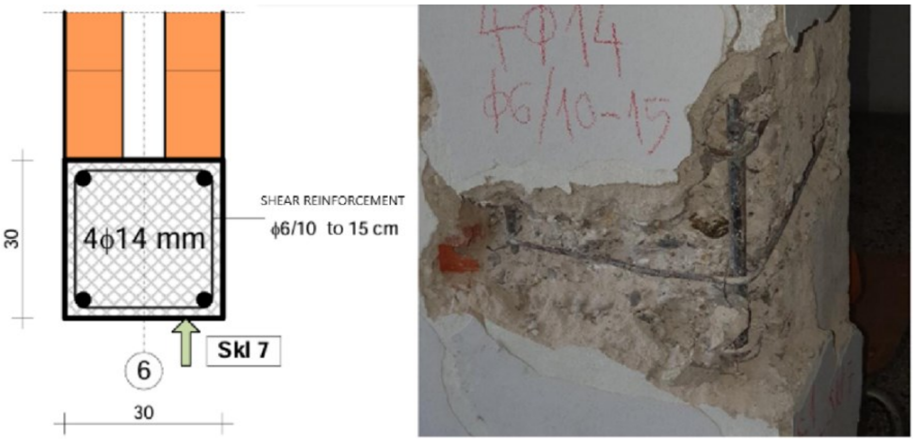

Figure 3. Reinforcement in the column [4]

3. Retrofit using base isolation

3.1. General

The idea is to achieve seismic safety of the building by using base isolation. It is planned to install sliding seismic isolators "Friction Pendulum" isolators. The installation of base isolation ensures the dissipation of energy in a controlled positions and a significant reduction of damage, especially during earthquakes of low intensity where buildings remain undamaged and functional, which is necessary for the operation of important institutions such as hospitals.

Base isolation increases the period of the structure to more than two seconds, which results in a smaller seismic force, but it is necessary to carry out the verification of the structure and the seismic force obtained after the installation of the isolators. The diagram in the Fig. 4 shows the positions of the isolators, where the two types of isolators differ depending on the force. Defined in manufacturer's data, two types of isolators used, have different horizontal stiffness, which is defined by vertical forces. As shown in Fig. 4 red positions are used to show isolators with greater vertical load, and positions colored blue show isolators with smaller vertical load.

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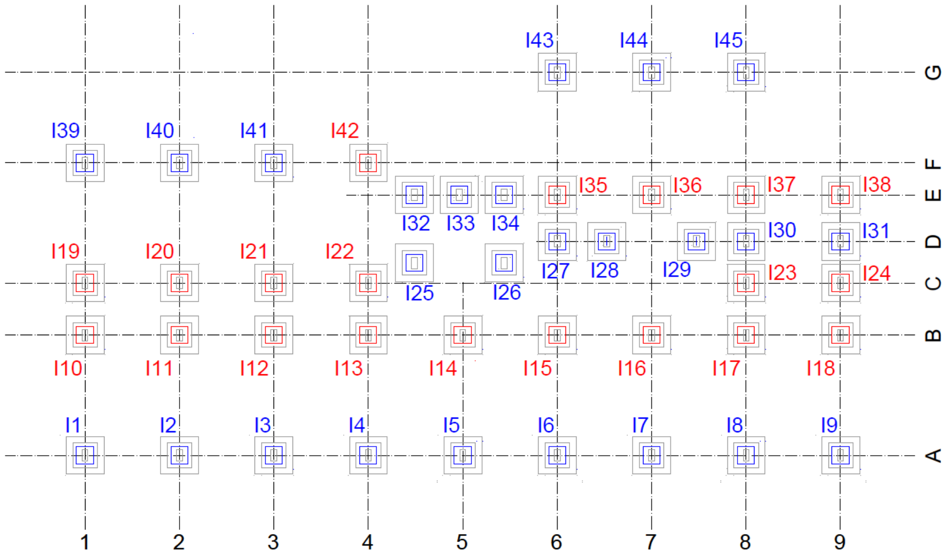

Figure 4. Layout diagram of the base isolation

3.2.Structural analyses

In the ETABS software [5], a numerical model of existing state of the structure was created. The isolators are modelled with "Link elements" with "Friction Pendulum" isolator behavior. An axonometric representation of the model is attached in Fig. 5. Parameters defined for “Friction Pendulum” isolators in ETABS are shown in Table 1.

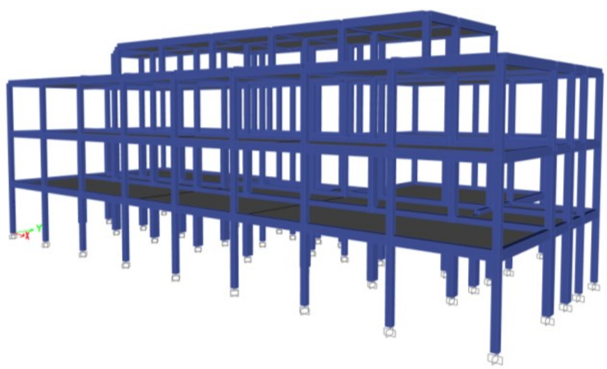

Figure 5. Axonometric view of the model [5]

Table 1. Parameters defined within ETABS

Parameters used in ETABS							
Isolator color	Vertical stiffness (kN/m)	Horizontal linear stiffness (kN/m)	Horizontal nonlinear stiffness (kN/m)	Friction coefficient, slow	Friction coefficient, fast	Rate parameter (sec/m)	Net pendulum radius (m)
Red	1275000	320	20800	0,0182	0,026	50	2,5
Blue	1275000	160	10400	0,0182	0,026	50	2,5

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The non-linear dynamic analyses of the structure is performed. An artificial strong motion record was matched to the elastic spectrum of the response increased by the importance class of the building (1,2). The peak ground acceleration corresponding on the location is 0.254g x 1.2 (importance class) [6], and soil is classified as type C. The damping used is 5%. Fig. 6 shows a 30-second record set in the X and Y directions.

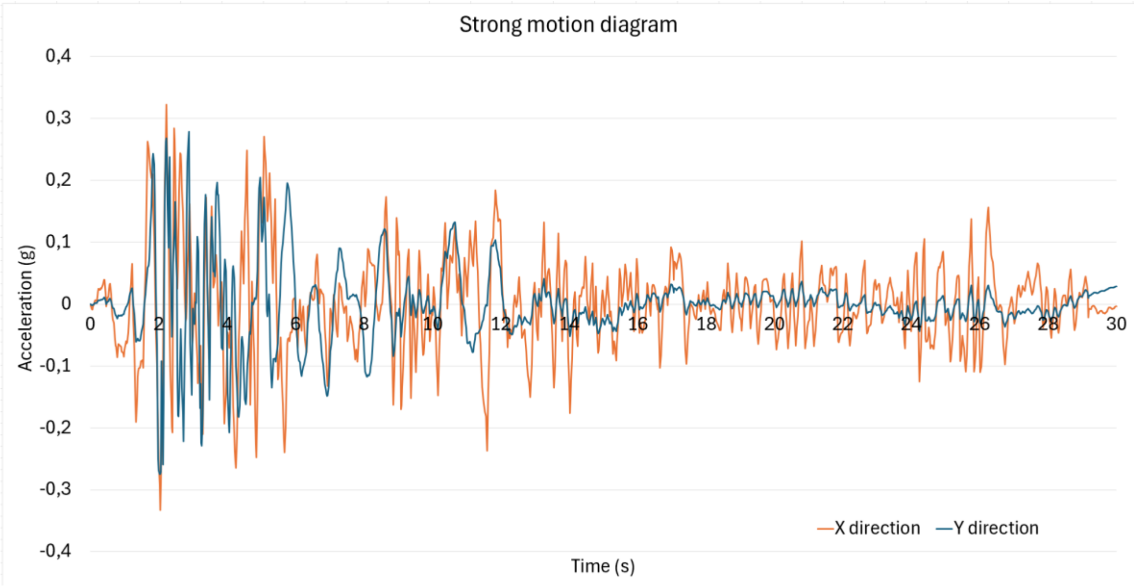

Figure 6. Time History function– X and Y direction

In the bilinear model according to Fig. 7 F_Y defines the critical transverse force required to initiate sliding, equal to the product of the axial force and the coefficient of friction. The ratio of the axial force and the radius of curvature defines the stiffness after yielding. The coefficient of friction depends on the sliding speed and initially increases exponentially, and then reaches a maximum value at a higher speed.

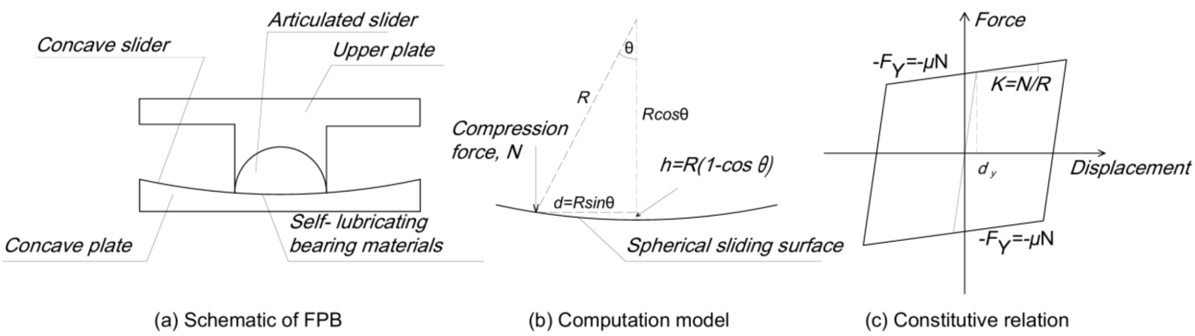

Figure 7. Schematics and behavior of „Friction Pendulum" isolator [7]

The building is freestanding and separated from neighboring buildings, and as such has the possibility of movement in all directions. For installing isolators, it is necessary to foresee and secure an adequate installation location, in this case it is necessary to construct a technical floor, as shown in Fig. 8.

The planned technical floor would be built at the height of the existing isolated foundations. The floor of the technical floor is planned as a reinforced concrete slab with a thickness of 15 cm. Above the position of the isolators, the installation of HEB 300 steel profiles and trapezoidal sheet metal is planned as lost formwork with a 6-centimeter thick reinforced concrete plate that acts as a

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horizontal diaphragm and ensures uniform structural movements. With this approach, seismic action is distributed to all isolators simultaneously.

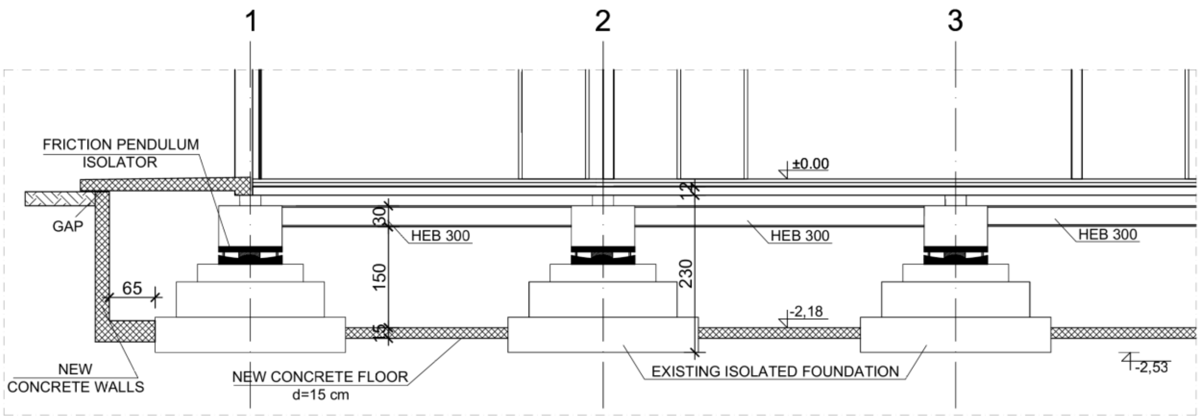

Figure 8. Elevation view of technical floor

3.3. Results

Below are presented the main results of the dynamic nonlinear analysis of the building and isolators. In Table 2. ten isolators with the biggest displacements are shown, with maximal displacement being 10,5 cm. According to the regulations, the displacement results must be increased by a factor of 1.2. Permitted displacement according to the manufacturer's instructions for selected isolators is 17 centimeters.

Table 2. Maximal displacement of isolators

Maximal displacements of Link elements										
Isolator tag	I9	I1	I2	I7	I3	I6	I5	I4	I8	I18
U2 (m)	-0,105	-0,105	-0,105	-0,105	-0,105	-0,105	-0,105	-0,105	-0,105	-0,104
U3 (m)	-0,085	-0,081	-0,082	-0,084	-0,082	-0,083	-0,083	-0,083	-0,085	-0,085

Table 3 shows the maximum forces that occur in isolators. It is important to choose type of isolator depending on maximal displacement and maximal vertical load that occurs on isolators. "Friction Pendulum" isolators cannot transmit tensile stress, so it is necessary to check the forces on the isolators. In table 3. "P" represents Axial force, "V2" force in X axis and "V3" in Y axis.

Table 3. Maximal force in isolators

Maximal forces of Link elements										
Isolator tag	I9	I1	I2	I7	I3	I6	I5	I4	I8	I18
P (kN)	-1180	-1176	-1151	-1145	-1139	-1132	-1122	-1089	-1031	-1022
V2 (kN)	-74,4	-74,7	-73,8	-65,0	-63,0	-72,8	-54,0	-61,8	-36,8	-45,5
V3 (kN)	-55,4	-54,9	-53,7	-51,9	-51,8	-52,4	-47,6	-65,2	-38,3	-44,8

It is important to compare natural periods of the structures. Building before retrofit had first structural period 1,04 s, second period 0,92 s and third period 0,85 s. Base isolated building has first periods 3,53 s, second period 3,50 s, and third period 3,25 s.

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The resulting shear force and horizontal displacement for isolator "I13" in the X and Y directions are shown in the Fig. 9 and correspond to the assumed hysteresis behavior of the isolator.

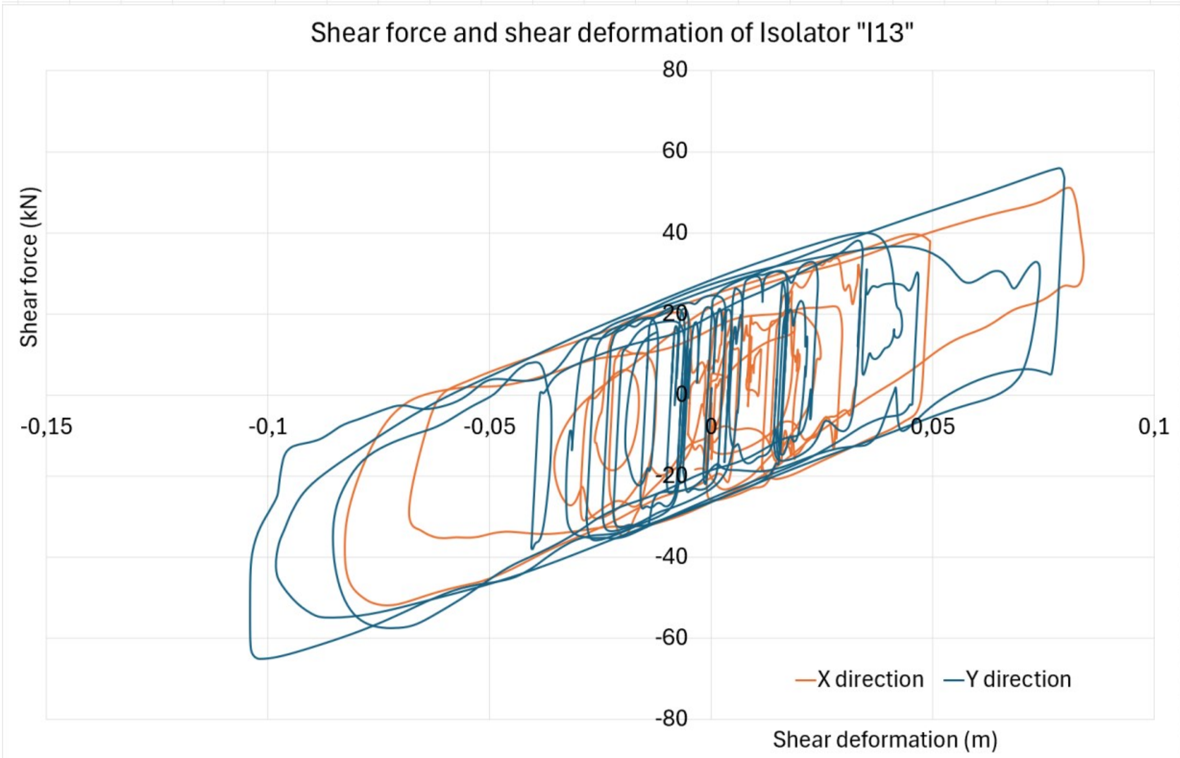

Figure 9. Shear force and deformation of Isolator "I13" in X and Y direction

Horizontal displacement in the X and Y directions for Isolator "I13" during the record is shown in Fig. 10.

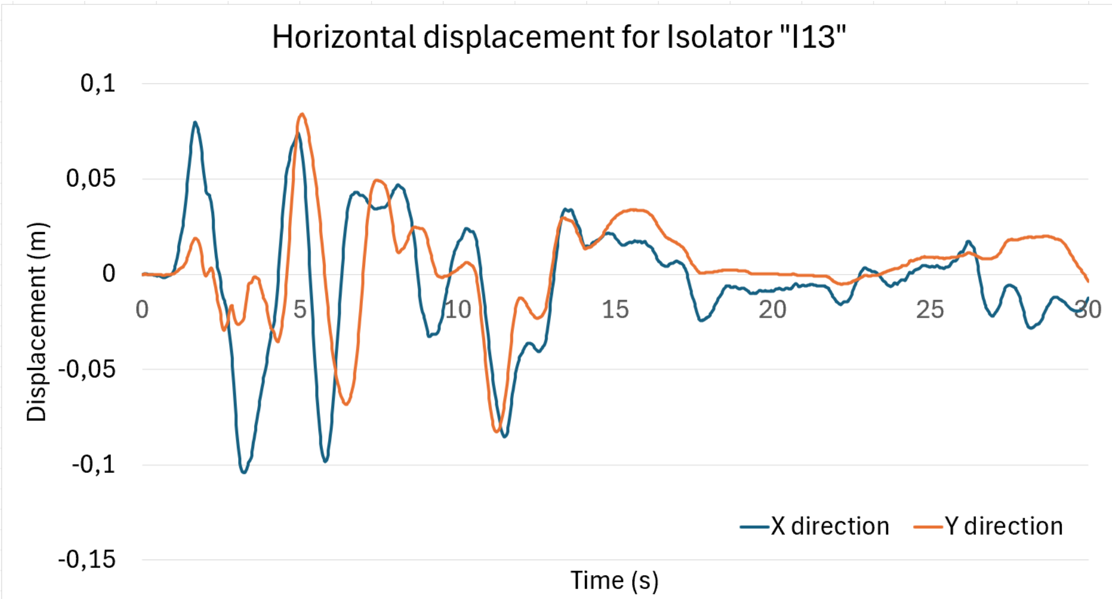

Figure 10. Displacement of Isolator "I13"

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4. Retrofit using conventional method by inserting RC walls

The structure was retrofitted with conventional methods which involves new reinforced concrete walls with new foundations, as shown in Fig. 11. The chosen concept does not require the reinforcement of columns and beams, but rather to minimize the structural displacements and equalize them so that the columns do not exceed the ductility requirements. The new walls relieve the existing frames and achieve greater rigidity of the building, provided that they are constructed continuously from the foundation to the roof and adequately connected to horizontal diaphragms. The connection to the rigid diaphragm was carried out through the existing beams - by drilling the existing beam and pulling the reinforcement through the beam, which also achieved vertical continuity of the walls for force transmission. Due to significant horizontal seismic forces on part of the new reinforced concrete walls, tensile stresses appear at the edge, which cannot be taken over by the existing foundation structure even with reinforcement. Therefore, it was necessary to install ground anchors that transfer the tensile forces to deeper soil.

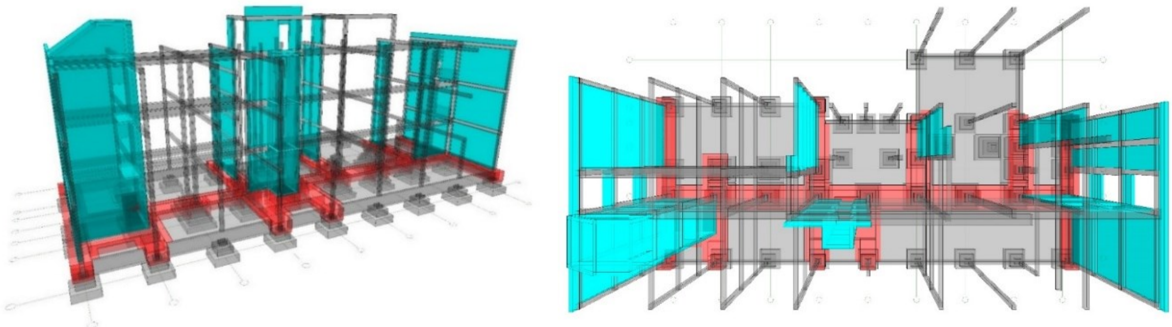

Figure 11. Structural retrofitting according to the reconstruction project [3]

Fig. 12 shows the complexity of the intervention, during reconstruction after the earthquake using the conventional method of inserting walls. The removal of floor and wall coverings on all floors in order to be able to access the reinforcement and new elements of the structure require moving out and the need for a replacement location.

Figure 12. East facade and ground floor during renovation [8]

5. Comparison of results

In this chapter, a comparison of periods, displacements and forces for two cases of reconstruction are shown.

Fig. 13 shows a comparison of the structural periods, the structure achieves a much larger period with base isolation, and thus a significantly lower seismic force. Reconstruction of the building using the conventional method with the insertion of walls adds rigidity to the building and thereby reduces the periods and increases the seismic force.

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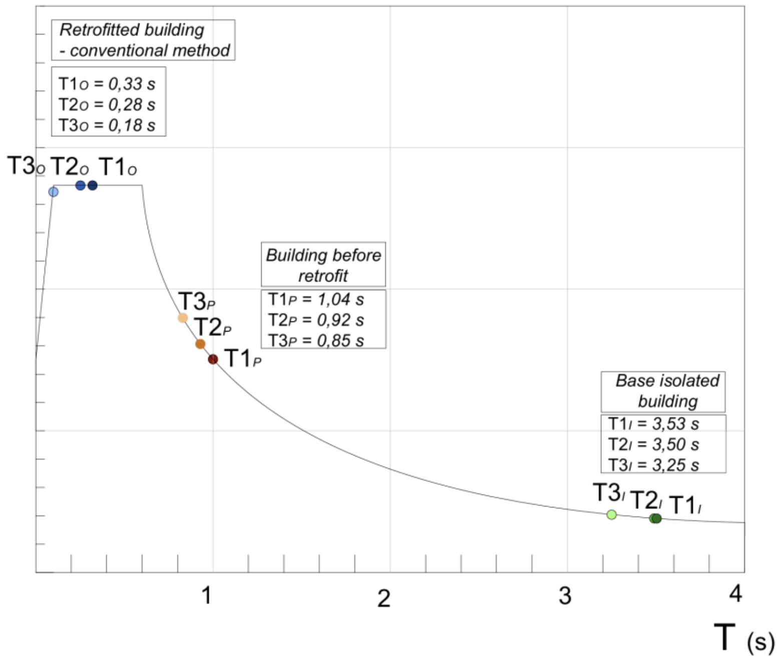

Figure 13. Comparison of construction periods

The Fig. 14 shows the structural displacements for all three models. The structure with base isolation has a large displacement in the isolator, which meets the manufacturer's allowed displacement, and the total displacement of the structure according to dynamic analysis is 17.1 centimeters, as shown in Table 4, so it is important that the building has the ability to move in all directions. Retrofitting by using conventional methods stiffens the structure, and displacements are small. When using base isolation, displacements are concentrated in the isolators.

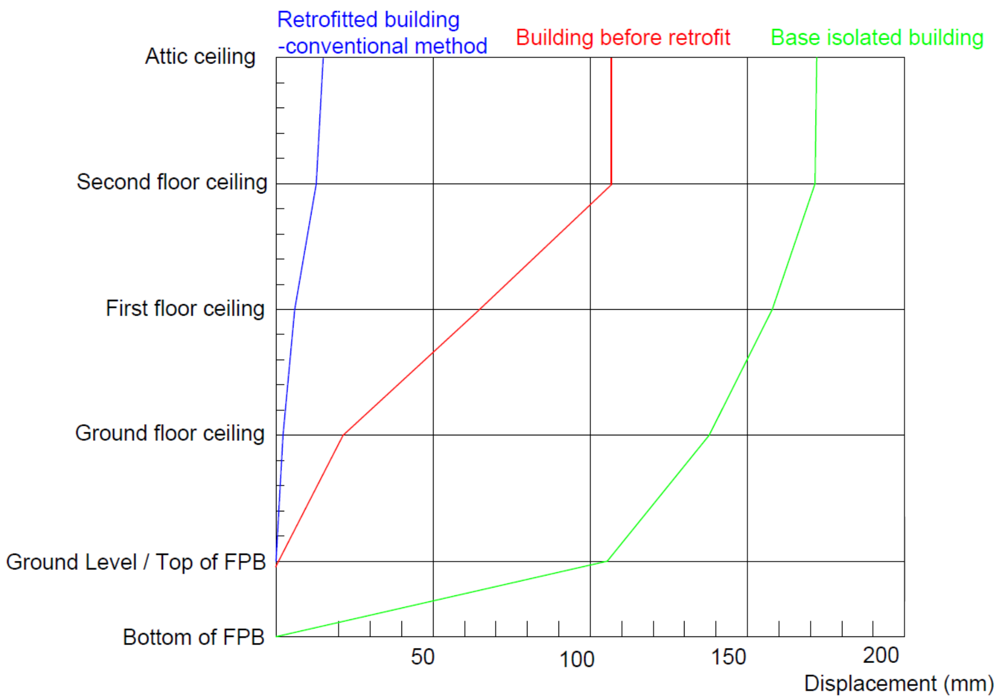

Figure 14. Comparison of displacements

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Table 4. Comparison of maximum story drifts

Displacement of the building before retrofit (earthquake)	10,7 cm
Displacement of the building with base isolation (earthquake) – dynamic analysis	17,1 cm
Displacement of the building after retrofitting by using conventional methods (earthquake)	1,2 cm

The difference between the shear force at the foundation level for the three models is shown in Table 5. As part of Table 5, the Base shear was calculated, which represents the horizontal force as a part of the total weight that is activated by seismic action. It is evident from the results that by using base isolation, we reduce the base shear of structure. Less energy dissipation through structural elements is required, and the structural elements in the model with base isolation have sufficient resistance to new seismic loads.

Table 5. Comparison of Base Shear between models

	Building before retrofit	Base isolated building	Retrofitted building – conventional method
Shear force (kN)	4944	2700	6720
Total weight (kN)	20760	22100	27680
Base shear	24%	12%	24%

5.1.Cost analysis

Building was analyzed based on the prices achieved on the market, as shown in Table 6. Structural reconstruction by inserting new RC walls amounts to only about 30% of the cost of the "complete reconstruction".

- Structural reconstruction costs around 900.000 €
- Other works around 2.100.000 €
- Total reconstruction 3.000.000 €

Table 6. Cost estimate on a building according to the reconstruction project

Recapitulation of construction works – strengthening by conventional method		
1.	Preparatory works	19.400,00
2.	Removal and disassembly works	222.410,00
3.	Renovation of existing structure	138.793,00
4.	Construction of ground anchors	26.160,00
5.	Construction of new foundations	181.093,83
6.	Construction of new reinforced walls and slabs	321.037,69
Construction works total:		**908.894,52**

By analyzing the cost items of other professions, it is estimated that other costs would be significantly reduced to around 40%. Reduction in other costs is achieved because floor and wall coverings on the upper floors are not affected by reconstruction. Removal and assembly of new installation for heating, cooling, gas, water and electricity is avoided, so existing installation remain. There is no need for moving furniture and equipment. The total savings of a complete reconstruction using base isolation would be more significant, as shown in Table 7:

- Structural reconstruction costs around 865.000 €

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- Other works around 840.000 €
- Total reconstruction 1.705.000 €

Table 7. Cost estimate on building with base isolation

Construction works recapitulation – construction with base isolation		
1.	Installation of isolators	308.000,00
2.	Removal and disassembly works	12.078,10
3.	Renovation of existing structure	40.592,00
4.	Construction of steel structure	168.000,00
5.	Excavation and foundation of the technical floor	196.022,00
6.	Construction of reinforced walls and pressure plate of the technical floor	140.437,90
Construction works total:		**865.130,00**

Except achieving resistance to seismic effects by using base isolation, it is necessary to consider other advantages:

- Except on the ground floor (where it is necessary to remove the entire floor covering and floor slab), no structural reinforcement work is carried out on the upper floors, so it is not necessary to remove the floor and wall coverings and subsequently install new and replacement ones.
- It is not necessary to move furniture, dismantle equipment and appliances, dismantle interior and exterior joinery and replace them with new ones, except on part of the ground floor.
- On the upper floors, the existing installations are not damaged during strengthening works.

Looking at the direct and indirect costs, advantages and disadvantages of the application of base isolation, we come to the conclusion that the retrofit using base isolation would be beneficial about 43% compared to the conventional methods of earthquake reconstruction with the addition of new reinforced concrete walls.

6. Conclusion

Until now, base isolation has not had a significant application in Croatia. In the paper, on a example of a building reconstructed after an earthquake, the possibility of ensuring the required seismic resistance according to legal regulations was considered by applying base isolation. In order to obtain realistic financial comparison, data from the realized project with the conventional method were used. The analyzed building typology belongs to the reinforced concrete frame structures built before the first earthquake regulations and which are being widely reconstructed after the recent earthquakes in the Zagreb and Petrinja areas. The reinforcement in the existing columns is insufficient, which is evident from the investigation works and confirmed by the analysis of the existing condition. Accordingly, strengthening measures for such a typology of the building require intervention in the existing structure and the construction of new ductile reinforced concrete elements that will take over the earthquake forces. This strengthening principle has increased the rigidity of the structure, which is evident from the reduced structural periods. The result is increased shear forces that need to be taken over by new reinforcement, continuously carried out and properly founded. After the reconstruction of the building, the significant damage index (IZO factor) met the legally required 0.75 values to achieve Level 3. In this paper, the analysis of the building using base isolation leads to a significant reduction of the shear force, which results in no need for straightening of the existing structure, and therefore no removal of most of the floor and wall coverings and associated installations, which is the main advantage of the reconstruction of frame structures using base isolation.

Furthermore, by applying base isolation, in addition to achieving sufficient seismic safety, damage during future earthquakes would also be reduced, and buildings could remain fully functional.

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This is especially important for critical infrastructure buildings that must remain functional during earthquakes. Base isolation plays an increasingly important role in the construction of new and strengthening existing buildings against seismic action worldwide, and it certainly deserves more significant application in Croatia, as presented in this paper.

Acknowledgments:

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