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Seismic isolation of buildings in Croatia

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Abstract

Following the destruction and panic caused by the earthquakes that rocked Croatia during the past year (all of which happening during a global pandemic), this work provides a brief description over the effectiveness of seismic isolation techniques in the region. To achieve that, we design, detail and analyse a six-story RC residential building, making use of the traditional capacity design approach and the seismic isolation approach, considering the local settings of seismic hazard and site characterization in the region of the capital city of Croatia, Zagreb. Furthermore, through Fast Nonlinear Analysis, the performance of seismically isolated building and the isolation system is verified with artificial Time Histories generated to match the spectrum of the design earthquake in the region. The shift in frequency of vibration and dissipation ability of the isolation system reduced the shear force induced in the superstructure in the case of the isolated building, allowing for a reduction in the cross-section and rebar area of the structural members which compensate for a part of the cost of isolation system. Moreover, the notably low interstory drifts in the case of seismically isolated building, ensure that no structural or non-structural member of the building sustain any damages at all, while the reduction of the floor acceleration enables a remarkable reduction in human perception of the seismic event, avoiding this way the panic or uncertainties that are common in the case of traditional design approach. Overall, given the country's relatively high seismic hazard, the structural analysis revealed a significant enhancement in structural performance, indicating that seismic isolation is very relevant in the region.

Key words: Zagreb earthquake, seismic isolation, base isolation, double concave curved surface sliders, pendulum isolators, fast nonlinear analysis, structural behaviour

1 Introduction

The earthquakes that struck Croatia during the 2020 combined with the lockdown forced by what it is an ongoing global pandemic, posed a great challenge to the authorities and the interdisciplinary scientific community to manage, analyse and overcome the situation. Unfortunately, the consequences of such a combination were high in terms of both human life and economical loss, as well as panic and uncertainty spread among the population [1–3].

The first major earthquake (M_L = 5.5) struck in the densely populated area of Zagreb on the 22nd of March 2020, causing extensive damages in the building stock and claiming the lives of two citizens [4]. Ironically, as people were continuously being asked to stay inside due to the pandemic, suddenly they were forced to get outside of their homes, dealing not only with the panic of the ground motions that continuously rocked the area, but also the fear and uncertainties already caused by the unprecedented pandemic. Furthermore, there were damages reported to the hospitals, that also forced the medical staff and the patients (some of them were being treated for Covid-19) to stay in tends or outside of the damaged facilities (Fig. 1). As it was reported in [5, 6], this combination of circumstances increased the panic and uncertainties contributing negatively in the overall health of the patients.

But just before the end of the year, on December 29, 2020, another earthquake, even more powerful (M_L = 6.2) rocked the area of Sisak and Petrinja, just 50 km from Zagreb. Unfortunately, this seismic event claimed the lives of 7 more people and caused even more damages to the building stock [3,7] (the evaluation process is still undergoing as this report is being written, February 2021).

Figure 1. Photo showing the medical staff and the 88 patients of a hospital in Zagreb evacuated from the damaged facility after the earthquake of 22nd of March. Source: [5]

While certainly earthquakes are not something extraordinary in Croatia [8,9], this unprecedented combination of a global pandemic and natural disasters is another reminder of the importance of not only to investigate and understand the reasons that lead to such consequences but most importantly to intervene in ways that mitigate or even avoid damages in such unacceptable rates in the future.

As it is well known in the literature, seismic engineering offers two main ways to make the buildings able to withstand earthquakes: the capacity design approach and the seismic isolation approach. These two design procedures employ a completely different strategy to withstand earthquakes which makes them render a completely different structural behaviour. Unlike the capacity design approach [10–12], which fits the structure with the necessary resistance and ductility level to withstand the design earthquake without collapse (eventually it can develop structural damages that can also result in being unfeasible to repair), the seismic isolation approach [10,13,14], manipulates the impact that the seismic event induces to the structure and is able to bear multiple cycles of design earthquakes without compromising the structural integrity of the building and keeping it in operational phase.

This work analyses the effectiveness of seismic isolation approach in the Croatian territory (more specifically in the Zagreb area) by designing, detailing, and analysing the structural behaviour of a residential RC building using the design provisions of the capacity design (as a benchmark), and the seismic isolation one. Taking into consideration the local settings of seismic hazard and site characterization of the Zagreb area, the analysis revealed a significant improvement of the structural behaviour indicating that the seismic isolation approach is perfectly relevant in the region. Moreover, the isolated structure is verified through FNA making use of artificial Time Histories generated from the spectrum of the design earthquake. The nonlinear analysis confirm the appropriate behaviour of the isolation system and the enhancement of the structural performance of the building.

2 Case of study

The building under investigation is a conventional six story RC building, designated for residential purposes, and is composed of five above ground floors and one underground floor serving as a basement. The building is regular in plan and elevation, with a minor shrink of the area in the top floor. To better understand the effectiveness of the seismic isolation approach in the region, the building is initially designed using the capacity design procedure (also referred as fixed base solution/building) whose performance is used as a benchmark. The architectural configuration of the building is the same in both solutions (capacity design and seismic isolation solution), while the structural configurations differs as explained in the following subsections. For the sake of the simplicity and data available, the building is set in Zagreb, the city centre, and the site is selected such that the design earthquake is 0.25g (of PGA_{Rock} in compliance with the Seismic Hazard map of Croatia [9], Fig. 2a) and the soil characterisation of Type C according to the EN 1998-1 [10] (Fig. 2b).

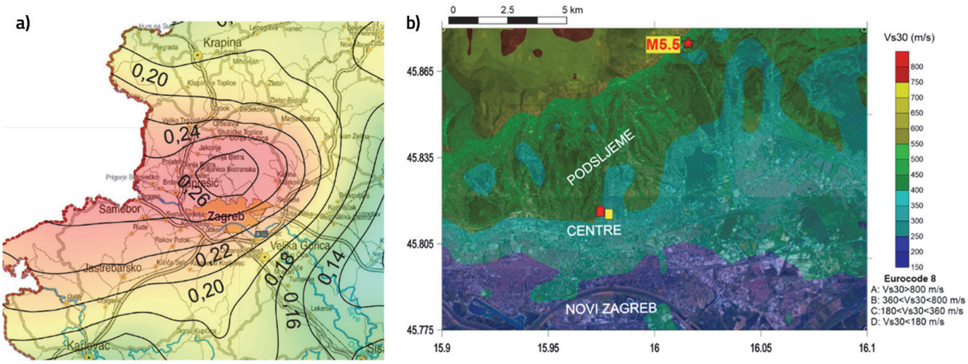

Figure 2. a) Seismic hazard map in the area of Zagreb for the 475 year return period earthquake in bed rock (Type A), acquired from [9], b) Soil type characterisation in terms of in the area of Zagreb, Source: [15]

2.1 Capacity design approach

The structural solution adopted in this case consists in a combination of shear walls, relatively large cross-sectional columns and a system of light weighted flat slab and perimetral beams stiff enough to ensure the diaphragmatic behaviour of the floors. The structure contains a rigid elevator case, made of RC walls, which induces high torsional effects in the structural behaviour, but necessary to give the structure enough stiffness to withstand the design earthquake. To minimise the torsional effects, an additional shear wall is set in the perimeter of the structure with relatively large dimensions (Fig. 2b).

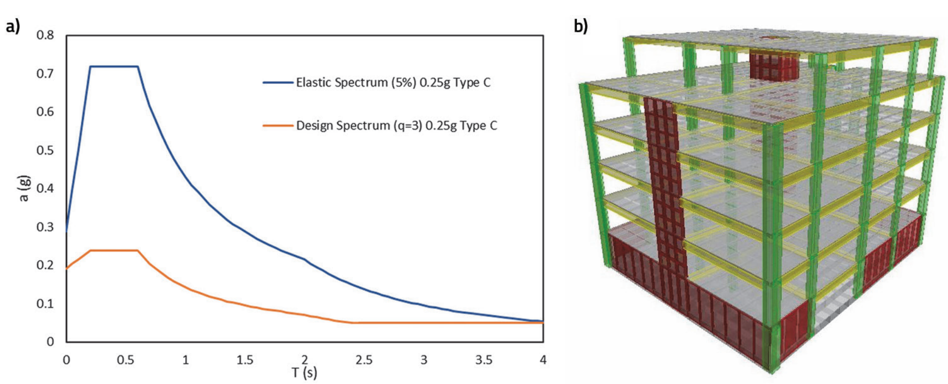

Figure 3. a) The elastic and design spectrum for the PGA_{Rock} = 0.25g in Type Soil C, b) Numerical model for the capacity design solution

The design spectrum is defined in compliance with the provisions of EN 1998-1 [10] for PGA_{Rock} = 0.25g in Type C category of soil, and the behaviour factor of the structure is selected q = 3 (Fig. 3a). Of course, such value of the behaviour factor means that damage of the structural members is accepted, provided that the building does not collapse.

2.2 Seismic isolation approach

In the case of the seismic isolation, the structural solution is simplified considerably due to the fact that the structural members of the superstructure don't have to be ductile to partially dissipate the energy of the earthquake.

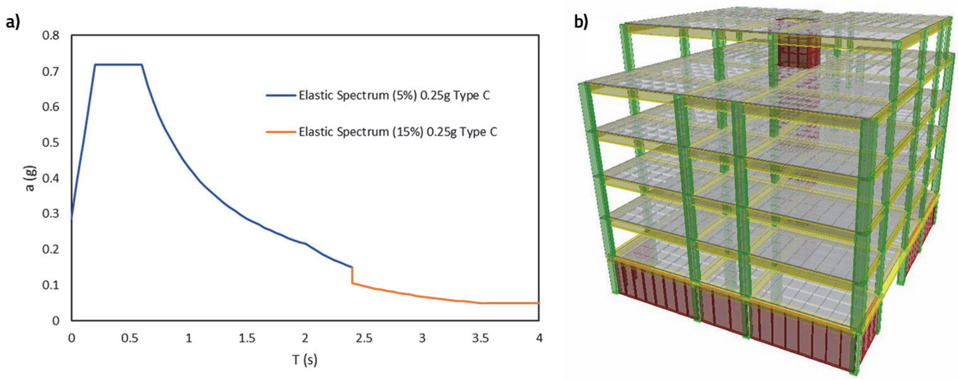

Figure 4. a) Elastic (design) spectrum for PGA_{Rock} = 0.25g on Type Soil C, b) Numerical model of the seismic isolation solution

Instead, the seismic isolation system strongly reduces the energy transmitted to the building by the earthquake, thanks to the increase of fundamental period to an area of the elastic spectrum characterised by very low acceleration, thus leaving the superstructure undamaged. The isolation system consists of 25 double concave curved surface sliders designed by FIP MEC to provide an equivalent damping coefficient of 15 % and a fundamental period of about 3 s at the horizontal displacement of about 15 cm. This allows for the superstructure to be designed and detailed in the linear range (in fact the design norms do not exclude the possibility of using the *Low Ductility* level q ≤ 1.5, but, for the sake of simplicity and remaining on the safe side, in this work the superstructure is designed and detailed for q = 1) using a response spectrum that is a composition of the elastic spectrum with 5 % damping for the higher modes of vibration, and the elastic spectrum with 15 % of equivalent damping of the isolation system for the isolated modes of vibration (as depicted in Fig. 3a).

2.3 Verification of the isolation system through nonlinear analysis

For design purposes, provided that the non-linearity of the isolation system is low enough to make the influence of the higher modes of vibration insignificant in the structural behaviour, a simple linear analysis is enough to properly design through the seismic isolation approach. On the other hand, in case that condition is not met, EN1998-1:2004 §10.9.5 (1)P [10] requires the verification of the behaviour of the structure through nonlinear analysis.

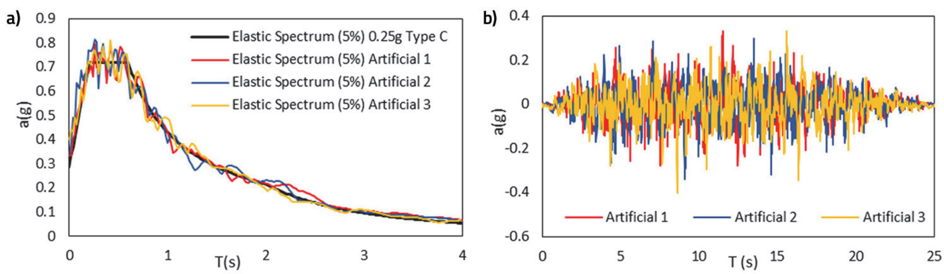

Figure 5. a) Response Spectrums of the artificial Time Histories generated from the design earthquake, b) Artificial Time Histories generated from the design earthquake spectrum

In the present case, the linearity conditions given by Eurocode 8 are satisfied, and consequently, it would be sufficient to rely on the linear analysis only. But, to better assess the effectiveness the isolation approach in the region, making use of artificial Time Histories generated from the spectrum of the design earthquake, the performance of the isolated building is verified through Fast Nonlinear Analysis carried out through the finite element software SAP2000 [16].

3 Results and discussions

In this section the structural response from the linear and nonlinear analysis of the case of study is provided.

3.1 Linear analysis

As expected, one of the most impressive differences in structural behaviour between the two solutions, stands in the principal modal parameters, as reported in Table 1. The shift in the period of vibration that the isolation system enables, significantly reduces the amount of shear force induced in the base of the structure (Fig. 6a). In the present case, the amount of shear force induced in the base of the structure is trimmed from about 5500 kN for the case of fixed base structure with behaviour factor q = 3, to about 2300 kN in the case of seismically isolated structure (designed in the elastic range, q = 1). Consequently, the reduced shear force allows for the reduction of the cross section and the rebar area of the structural members, which saves space and reduces the costs of the superstructure. Moreover, the modal analysis reveals that the isolation system allows for almost a perfect balancing of the structure, avoiding completely torsional effects, which further facilitates the design, detailing and delivering of the superstructure of the isolated building.

Table 1. Modal information of the case of study

Case | Mode	Mode 1		Mode 2		Mode 3	
	T [s]	**M** [%]	**T** [s]	**M** [%]	**T** [s]	**M** [%]
Fixed Base	0.69	68 % - X	0.65	73 % - Y	0.51	Torsion
Isolated	3.04	95 % - X	3.03	99 % -Y	2.86	Torsion

But the ability to shift the period of vibration comes with the consequence of having relatively large horizontal displacement to accommodate. However, in the case of base isolation solution, these displacements are concentrated in one single layer (while in the case of fixed base solution they are distributed in elevation as depicted in Fig. 6b). This causes the super structure to move as an entire rigid body on top of the isolation system. Therefore, proper considerations must be done to accommodate such displacements (accounting also for the safety factor recommended by the Eurocode): not just the isolation system but also the gap/infrastructure around the building must be configured in such a way that permits these displacements throughout the entire life span of the building..

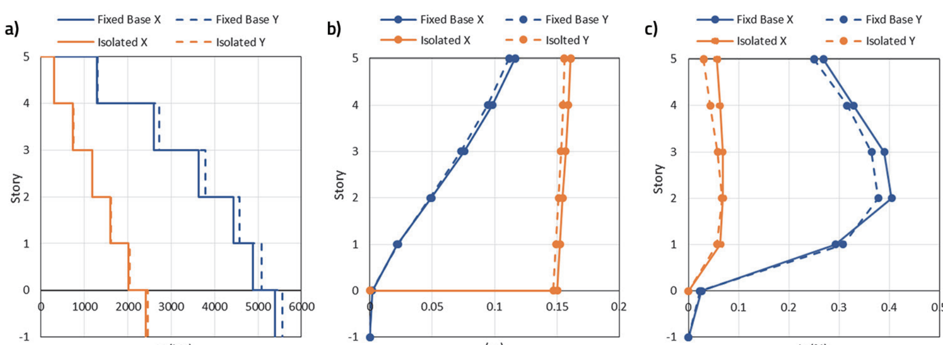

Figure 6. a) Story shear force, b) Lateral displacements, c) Maximum interstory drifts ratio

Generally, in structural engineering, limitation of the potential damages that the structure can develop is measured through the value and the distribution of the maximum interstory drifts ratio. In the present case, the fixed base solution is designed such that the maximum drift ratio are in compliance with the recommendations of European norms for buildings having non-structural elements of brittle materials attached to it (Fig. 6c). Unsurprisingly, the linear analysis revealed a significant reduction in the interstory drifts ratios induced in the super structure of the isolated building. It is worth to bring to attention that not only these drifts are significantly smaller than the fixed base solution, but also, they are estimated completely in the linear range given that the superstructure is designed in that domain. This ensures that the superstructure in the case of the seismic isolation approach remains completely unaffected, and the building remains in the operational phase even during the earthquake. Moreover, the isolation system is able to bear multiple cycles of design earthquakes, unlike the capacity design approach which is expected to develop structural and non-structural damages which might result to be non-feasible to repair (in any case, provided that the design is done correctly, the lives of the occupants must remain safe).

3.2 Fast Non-Linear Analysis

By means of FNA conducted in SAP2000, the numerical model of the isolated solution is analysed under the action of three artificially generated Time Histories. The artificial Time Histories are combined in artificial earthquake scenarios as reported in Table 2.

Table 2. Combination of artificial Time Histories in simulated earthquakes cases

Earthquake Scenario	X – Direction	Y – Direction
Scenario 1	Artificial TH - 1	Artificial TH - 2
Scenario 2	Artificial TH - 2	Artificial TH - 3
Scenario 3	Artificial TH - 3	Artificial TH - 1

As expected, the superstructure moves as a rigid body above the isolation system, having concentrated all the displacement in the isolation system (Fig 7a). While considering the floor accelerations, the isolation system prevents its amplification in elevation. In fact, Fig. 7 b) clearly depicts a reduction of the accelerations in the building (in absolute terms), from about 3.5 m/s^2 to 4 m/s^2 that the ground accelerates, the superstructure accelerates in the ranges of 1 m/s^2. This represents an enhancement in behaviour of the structure, which in a real seismic event, would reduce the perception of the seismic event in such a rate that would have not caused any panic at all, and save the content, i.e. avoid the overturning of furniture.

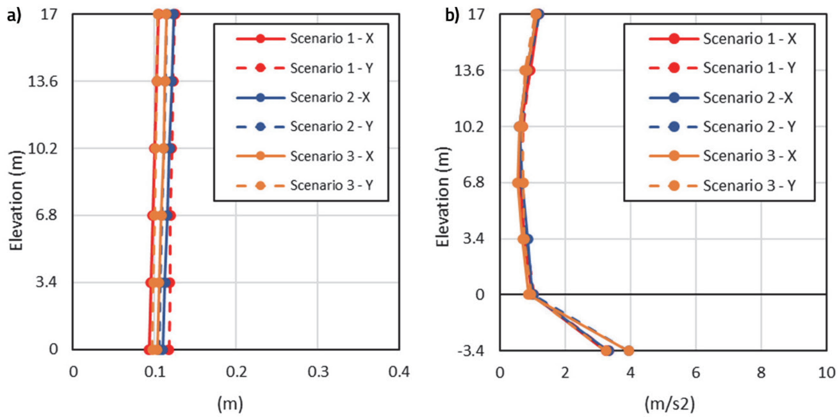

Figure 7. a) Maximum horizontal displacement b) Distribution of the floor accelerations

Moreover, Fig. 8 depicts a comparison of the acceleration of the top floor of the building to the acceleration of the ground (Artificial TH - 1 of the first earthquake scenario), where it can be seen the significant reduction of the floor acceleration throw-out the whole seismic event. The decrease of frequency/increase of fundamental period is also evident in the graph.

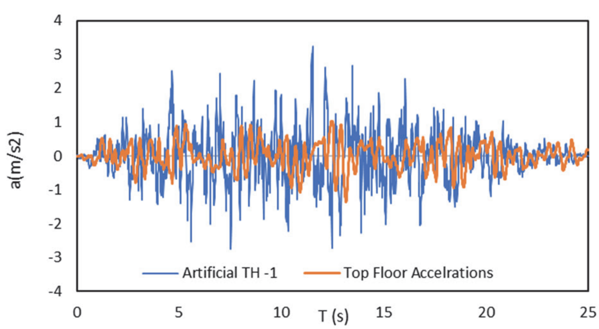

Figure 8. Comparison of the floor acceleration in the top floor of the building to the acceleration of the ground

Fig. 9 depicts the hysteretic loops of two isolators incorporated in the isolated building. Isolator in Fig. 9a attains a friction coefficient 2.8 % and therefore dissipates more energy compared to the isolator in Fig. 9b which attains a friction coefficient of 0.08 % attenuating the corresponding amount of energy. The average friction coefficient of the isolation system is 1.766 %.

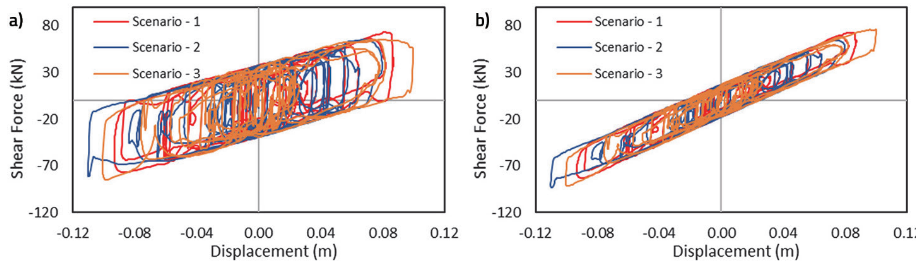

Figure 9. Isolator Hysteresis: a) Friction Coefficient 2.8 %, b) Friction Coefficient 0.08 %

4 Conclusions

The unprecedented combination of a global pandemic and the seismic events that struck Croatia during the past year, brought into attention the high seismic vulnerability of the country, mainly a consequence of the old building stock and relatively high seismic hazard. Joining in the attempts to find ways to mitigate the effects of seismic events in Croatia, this work provides an overview of the effectivity of seismic isolation approach in the region as an alternative of designing/delivering buildings with seismic protection. For this reason, an ordinary midrise reinforced concrete building designated for residential purposes as a sample building and considering the regional settings of seismic hazard and site characterization.

As expected, the seismic isolation offers a significant enhancement in the structural behaviour. The shift in the period of the vibration of the structure decreases the amount of the shear force induced in the superstructure to less than 50 % of the shear force that the same earthquake induces to the same building solved based on the capacity design approach. This allows for the reduction of the cross sections and rebar area of the structural members, increasing the overall useful area of the building and compensating for a part of the cost of the isolation system. The linear analysis revealed a significant reduction of the interstory drift ratio in the isolated building, which ensures the structural and non-structural members of the superstructure to remain completely unaffected even when the design earthquakes strikes. Moreover, the seismic isolation provides the opportunity to bear multiple cycles of design earthquakes, in contrast to the capacity design approach that is required to ensure the life safety performance level for only one design earthquake.

The nonlinear analysis with the artificially generated time histories, confirmed the relevance of seismic isolation in Croatia. The adequate behaviour of the seismic isolators is verified, as the nonlinear analysis rendered, with max horizontal displacement within the design values designed, no amplification of the floor accelerations in elevation.

Overall, the analysis reveal that the level of seismic hazard in the Croatia is high enough to make seismic isolation an efficient building option in the region not just for strategic buildings such as hospitals, but for small residential buildings as well. The enhancement in structural performance compared to the capacity design approach, also verified via nonlinear analysis with artificial spectrum based time histories, would strongly reduce the effects of future earthquakes.

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