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SEISMIC RETROFIT OF R.C. BUILDINGS IN USE THROUGH SEISMIC ISOLATION. THREE CASE STUDIES IN L'AQUILA, ITALY.

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Abstract

Seismic isolation (SI) advantages for new buildings are well known: not only it allows to avoid damage of both structural and non structural elements under strong earthquake, but it mantains building functionality as well. This is possible thanks to strong reduction of accelerations and interstorey drift in the superstructure, i.e. the part of structure above the isolation layer.

SI offers additional advantages for seismic retrofit of existing buildings. The main advantage is that the works can be limited at one floor (usually the basement, plus the foundation), without any strenghtening on the superstructure. Consequently, the building can be used during the retrofit works.

The safety of the retrofitted building increases significantly. Reaching exactly the same safety level of a new building in the same site would be possible, but it would need some strenghtening in the superstructure, and thus is usually avoided in order to keep the building in function during the works. It is worth noting that for the seismic isolation system, the safety is the same than for a new building.

The paper presents in detail three case studies of framed r.c. buildings built in the 1980s and now under retrofit with seismic isolation, that could be representative of many other buildings. During 2009 L'Aquila earthquake, those residential buildings were only slightly damaged, and immediately repaired but without any improvement of their seismic performance. Now the retrofit design is carried out for an earthquake stronger than the 2009 earthquake. Despite the buildings are in the same area (a_g=0.261g for the Life Safety Limit State earthquake; a_g=0.334g for the Collapse Limit State earthquake, used to design the seismic isolation system), the design spectrum is different because of different type of soil. The isolators are inserted in the basement or in the ground floor that host the garages, thus without affecting the apartments. The safety level reached in the three buildings was higher than 70% of that of new buildings in the same site, while before retrofit it was lower than 16%.

Keywords: seismic isolation, seismic retrofit, building

1. Introduction

Seismic isolation (SI) advantages for new buildings are well known: not only it allows to avoid damage of both structural and non structural elements, thanks to strong reduction of accelerations and interstorey drift in the superstructure, i.e. the part of structure above the isolation layer, but it allows to mantain building functionality as well, even under strong earthquake. That is why its use in strategic buildings - e.g. hospitals - is increasing everywhere in the world, including developing countries. In Turkey, seismic isolation is mandatory for large hospitals in high seismic areas. In Italy, seismic isolation of buildings is not anymore limited to strategic or public buildings; it is continuously increasing for residential buildings as well, in particular in areas with high seismicity, in which the additional cost of seismic isolation is compensated by the savings in the superstructure, and thus the global cost could be the same or lower of that of a conventional structure, but with much higher performance. Amongst a total of about 900 seismically isolated buildings in Italy until summer 2022, almost one half are residential buildings [1].

The strong reduction of acceleration provided by SI is of course beneficial to existing buildings as well; consequently, seismic retrofit of buildings with SI is carried out all over the world since the 1980s [2]. In Italy, seismic retrofit of buildings with SI became relatively common after the 2009 L'Aquila earthquake, initially on buildings strongly damaged by the earthquake. Recently, retrofit with SI is continuosly increasing, even in areas not recently affected by earthquakes. One additional

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advantage of retrofit with SI, in comparison with other conventional approaches, is that the works can be limited at one - two levels (usually the basement and the foundation level in r.c. buildings), without any strenghtening intervention on the superstructure. Consequently, the building can be mantained in use during the retrofit intervention. Moreover, the cost of intervention is reduced, in particular the cost portion not related directly to the structural intervention, but to demolition and refurbishment of non-structural parts. Mezzi and Petrella [3] report a cost comparison of alternative seismic retrofit strategies for two RC buildings damaged by the L'Aquila earthquake, showing that the strategy with seismic isolation allowed a saving higher than 30%. Now the Italian buildings retrofitted with SI are about 1/3 of the total number of seismically isolated buildings [1].

The safety of a building retrofitted with seismic isolation can become almost equal to that of a new building in the same site, i.e. with a Capacity/Demand (C/D) ratio equal to 1 or very close to 1. Reaching the same safety level (C/D=1) would be technically possible, but it would make necessary some intervention in the superstructure, and thus is usually avoided in order to keep the building in function during the works. However, it is worth noting that in Italy, for the seismic isolation system, the safety shall be the same than for a new building, even though the C/D of the superstructure is lower than 1. Furthermore, a specific Limit State (Collapse Limit State) is introduced by the Italian Code, i.e. the earthquake used for the design of seismic isolation system has an higher return period than the earthquake used for the design of the building. This approach substitutes in Italy the reliability factor required by Eurocode 8 on the displacement of the isolation system (1.2 recommended value for buildings).

2. Seismic retrofit through seismic isolation: case studies in L'Aquila

The paper describes 3 case studies of seismic retrofit of r.c. buildings with SI. The buildings, built in the 1980s, are residential buildings located in L'Aquila, that were only slightly damaged by the 2009 L'Aquila earthquake, and immediately repaired but without any improvement of their seismic performance. Taking the opportunity of the tax reduction offered by the Italian state in 2020, the owners decided to improve the seismic performance of the buildings, but requiring to keep the apartments in use during the works. Seismic isolation was thus selected as intervention strategy in all these buildings, with works at the garage level (basement or ground level) and foundation. The position selected for the isolation system is different in the 3 buildings, that thus become representative of many other buildings. It is important to note that a very short work time was imposed by the tax reduction law, and that energy redevelopment was carried out together with seismic retrofit: the fact that the structural works are located at one story only (ground story or basement, and foundation) has allowed to reduce a lot the total working time, because the seismic retrofit was carried out at the same time that the external thermal insulation.

The types of seismic isolators mostly used in buildings in Italy are elastomeric isolators (with high damping rubber) and curved surface sliding isolators (pendulum isolators). In retrofit of existing buildings, pendulum isolators are more frequently used, because they allow to reach high value of isolated period for any kind of structure. However, in these case studies the seismic isolation system comprises high damping rubber bearings (HDRB) and free sliding bearings. The latter are often used in Italy combined with HDRB, for two main reasons: they allow to increase the fundamental period even in low-rise buildings, and they make easier the reduction of eccentricity between center of mass of the superstructure and center of stiffness of the isolation system in very irregular structures. The equivalent viscous damping offered by HDRB is 15%. Linear analyses is admitted with this isolation system by both European and Italian standards. According to the standards, the damping is taken into account reducing the design spectrum for periods higher than 80 % of the fundamental period of the isolated building. The design spectra for the seismic isolation system of the 3 case studies are reported in Figure 1. Despite the buildings are in the same area, the design spectrum is different because of different type of soils. For Case Study 1, the soil is better than for the other two buildings. The difference between the spectra of case study 2 and 3 is only due to the different fundamental period of the isolated building selected in the design phase.

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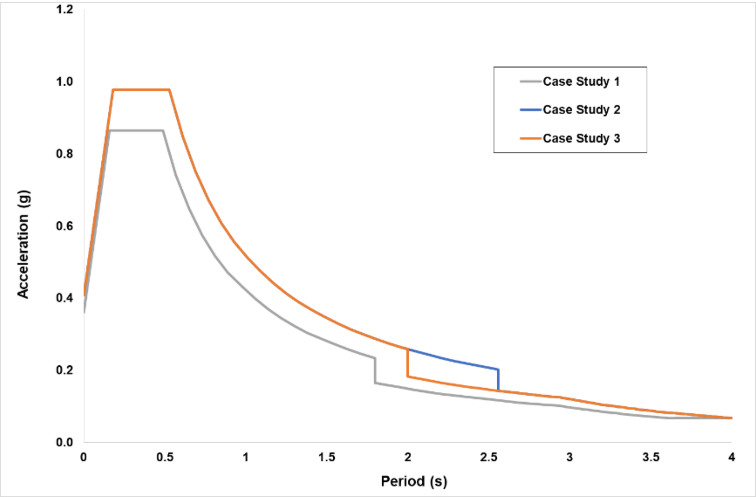

Figure 1. Design spectra for the three seismic isolation systems (at Collapse Limit State).

3. Case study 1: Crefel building

The building includes three units, built at the end of the 1980s with structure in reinforced concrete. Unit A and B are identical, with 6 floors, an height of 14 m and plan size 28.5 m x 12.5 m. Unit C has one floor only, and connects units A and B (Fig. 2 and Fig. 3). The r.c. structure is framed but includes shear walls as well (around the elevators). The foundations are ground beams. Both the infill and partition walls are masonry walls.

Units A and B have been seismically isolated, while Unit C strengthening has been conventional. In order to allow the big horizontal displacement associated with seismic isolation, a proper gap has been realized around the building, and of course Unit C has been disconnected from Units A and B. New steel columns have been inserted to sustain the floor of Unit C where the new seismic gap has been created, and the sidewalks were modified to cover the gap and allow the displacements at the same time.

Figure 2. CREFEL Building

The isolators have been installed on top of the columns of the underground floor, where the garages are located (Fig. 3). As it is well known, for a proper functioning of seismic isolation in a building, a stiff floor below and above the seismic isolation layer shall be guaranteed. In this case, the existing ground floor, immediately above the isolation layer, is stiff enough. Below the isolators, the needed stiffness is guaranteed by the foundation and the columns properly stiffened through an increase

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of their section. The steps followed for the installation of the isolators in each column are shown in Fig. 4 and described here below:

- enlargement of the column in the portion below the isolator, leaving proper recesses to be used for the lower anchorage of the isolator with dowels;
- core drilling of the upper part of the column, and insertion of ferrules to connect to the column the steel brackets that will serve to transfer the vertical load to hydraulic jacks;
- placing of hydraulic jacks to unload the portion of column to be removed; the load is transferred to foundation through provisional steel columns;
- diamond wire cutting and removal of the segment of the column where the isolator will be installed;
- levelling of the lower surface, and installing the upper anchorage of the isolator; this is a steel structure that embraces the column, to trasfer to it the shear force transmitted from the isolator;
- fixing the isolator to its upper anchorage, then grouting of the upper anchorage with antishrinkage cement or epoxy resin mortar;
- placing of non-returnable flat jack to load the isolator;
- final grouting of the bottom anchorage, including the non-returnable flat jack;
- removal of external hydraulic jacks.

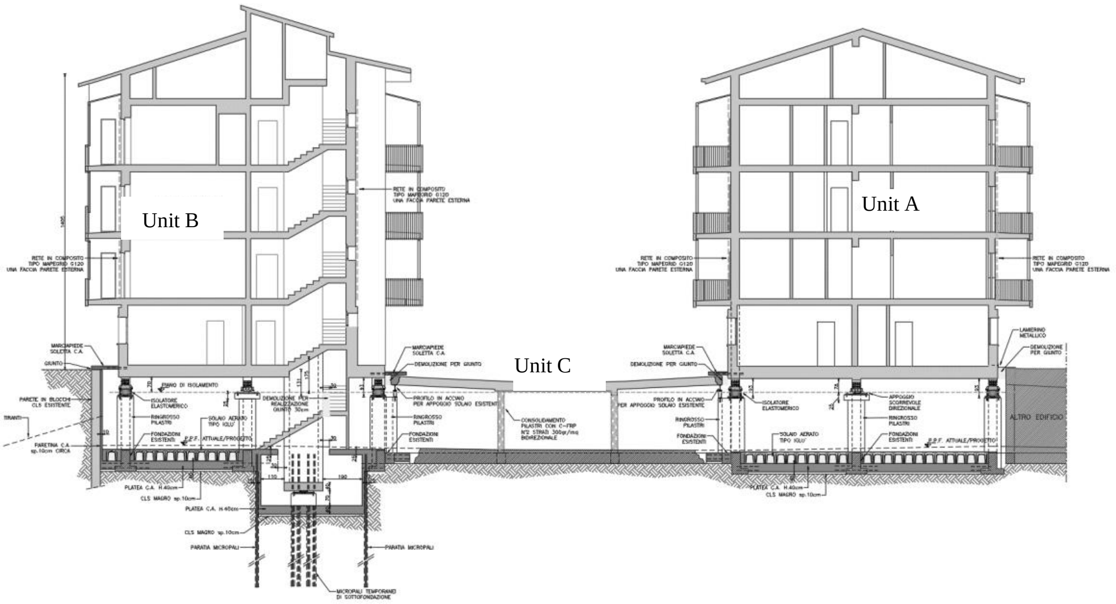

Figure 3. Cross section of Crefel Building.

The seismic isolation system includes 28 elastomeric isolators, type SI-N 450/98, and 10 free sliding pot bearings (Fig. 6), with displacement capacity of ± 200 mm. The pot bearing are installed in the central columns of each unit, and below each elevator; the elastomeric isolators in the perimetral columns, in order to guarantee a proper torsional stiffness of the isolation system. Of course the position of elastomeric isolators and sliders is selected with special attention at reducing the eccentricity between center of mass of the superstructure and center of stiffness of the isolation system. Said seismic isolation system allows to increase the fundamental period from the original value of 0.80s to 2.47s, and consequently to significantly improve the building's seismic response. Said "improvement" has been quantified in about 65% (C/D changed from 0.09 to 0.76). In terms of seismic risk classification [4], the seismic risk class changes from F for the original building to B for the seismically isolated building.

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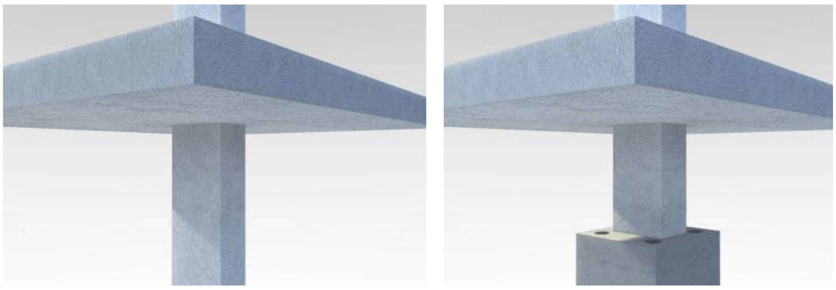
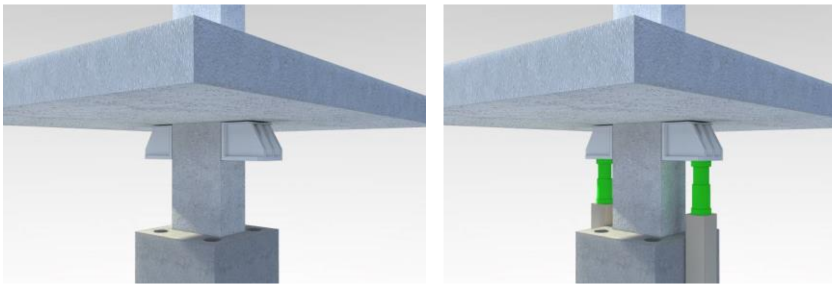
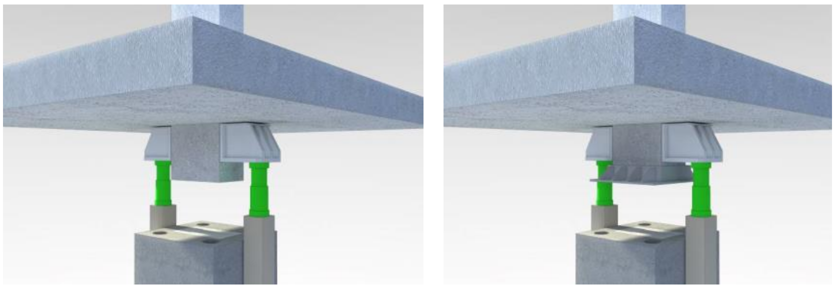


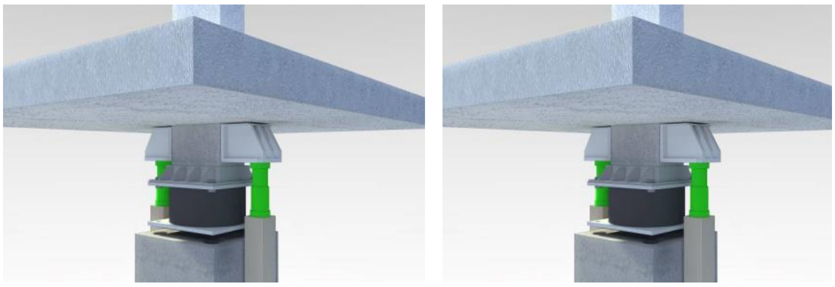
1) the column before retrofit; 2) column enlargement;



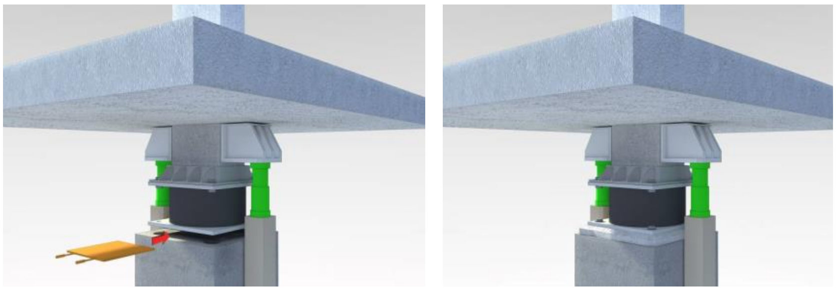
3) fixing of steel brackets; 4) placing of hydraulic jacks;



5) cutting and removal of column segment; 6) insertion of upper anchorage structure;



7) isolator fixed to upper anchorage structure;8) grouting of upper anchorage structure;



9) insertion of non-returnable flat jack; 10) final grouting of the isolator.

Figure 4. Steps for isolators installation in Crefel Building.

Figure 5. Crefel Building: two phases of the installation of the isolators.

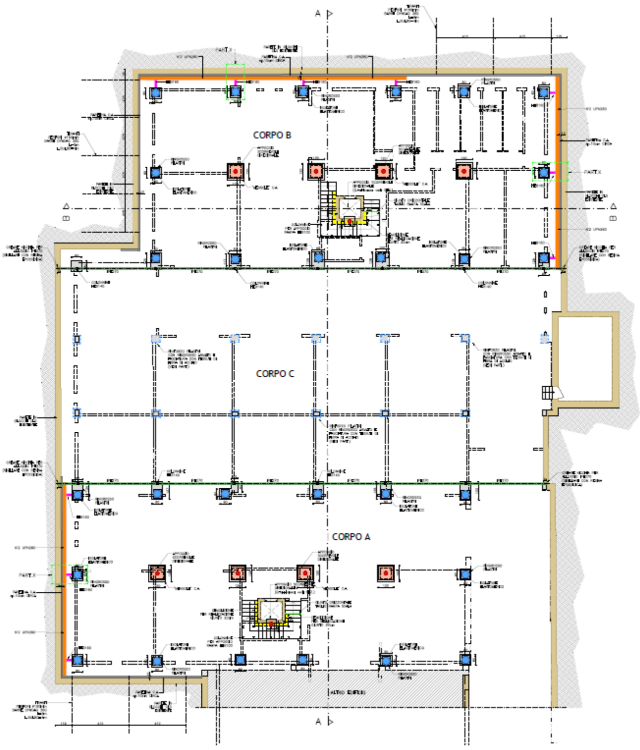


Figure 6. Plan of the isolation system for Crefel Building.
Elastomeric isolators are in blu, free sliding pot bearings in red.

4. Case study 2: building in via Di Vincenzo 23

The building has 5 floors, with garages at the ground floor (Fig. 7). It has total plan size 56 m x 16 m, is built in the first 1980s with r.c. frame. It includes two units, separated by a structural joint of about 20 cm. For this building it was not possible to insert the isolators at top of the columns of the garages, as in previous case, mainly because the height of ground floor was not enough to have the isolation level above the garage doors. Consequently, the isolators have been inserted at the foundation level, and a new floor was built above the isolators, acting as new ground floor (Fig. 8).

The isolators have been inserted at the base of the columns, modifying the existing foundations. Fig. 9 shows all the steps executed for the modification of the foundation system and the installation of the isolators. At the base of each column, part of the foundation has been cutted in order to create the space needed to insert the isolator. Furthermore, new micropales are inserted, new plinths are created under each column, to serve as basis for each isolator, and a new foundation slab is made to connect the plinths. Of course all these activities shall be carried out with care, to allow the transfer of load from

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old to new foundations, through the isolators. The columns are reinforced as well, at the ground level, in order to increase their strength; this is important in particular to resist local actions during works.

The joint between the two built units was left as it is in the superstructure, but it was eliminated at the floor immediately above the isolation layer, to guarantee that the two units will move together during earthquake. This is usually done in seismic isolation of existing buildings, because the existing gap would not be enough to accomodate the horizontal displacement of each seismic isolated building unit, that of course is much larger than in the fixed base building. Furthermore, even in new seismically isolated buildings, it is quite common to eliminate completely the internal seismic joints amongst different built units, or keep them just as thermal joints in the superstructure, in order to avoid the difficulties and costs of large seismic joints.

New perimetral retaining walls and special sidewalks to allow the horizontal displacement of the building complex were built.

Figure 7. The building in via Di Vincenzo 23.

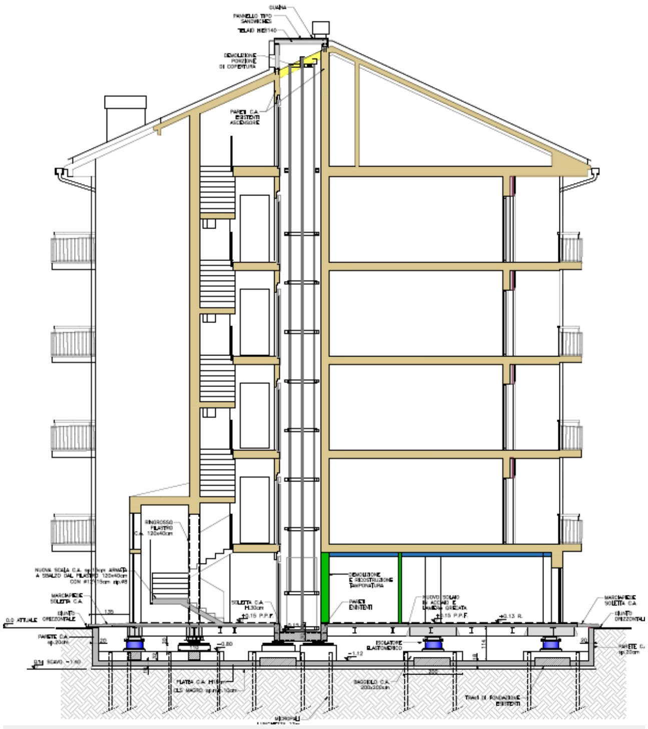
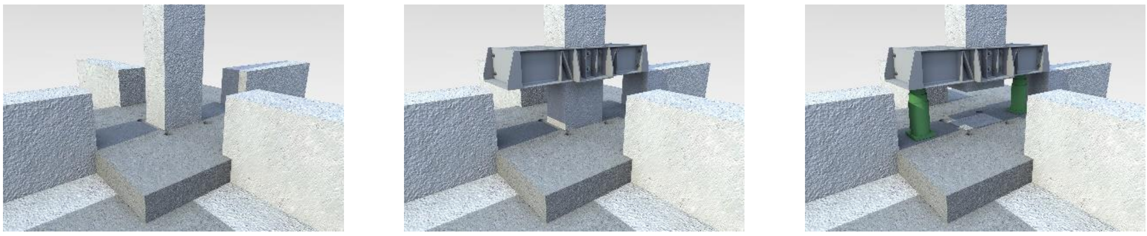


Figure 8. Cross section of the building in via Di Vincenzo 23.
Elastomeric isolators are in blue, free sliding bearings in black.

1) before intervention;

2) insertion of micropiles;

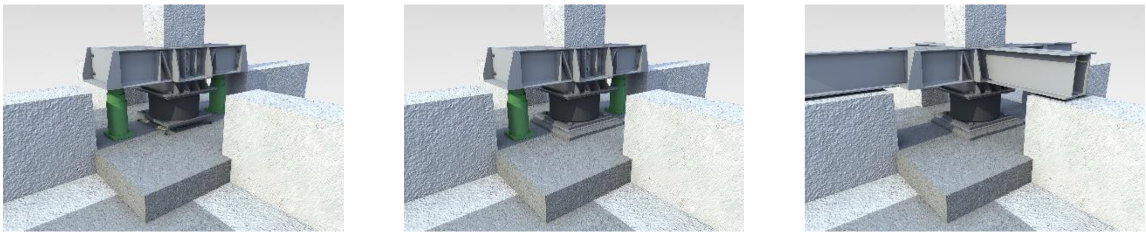
3) new plinth between the column and the micropiles;



4) cutting of part of foundation around the column;

5) insertion of steel structure for upper anchorage of the isolator;

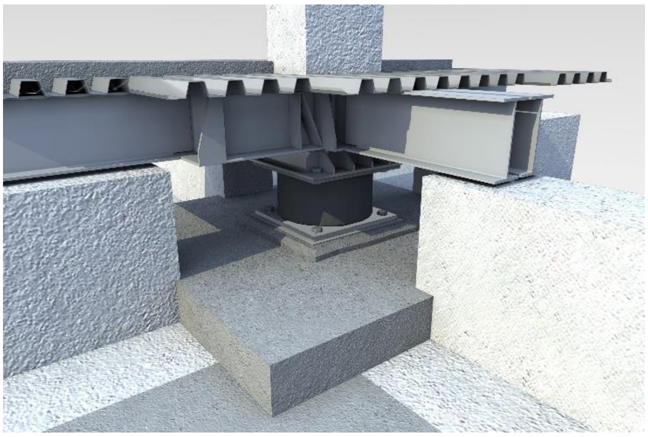
6) insertion of hydraulic jacks, transfer of loads, and cutting of column;



7) insertion of the isolator;

8) loading of non-returnable flat jack & grouting of the isolator's bottom ancorage;

9) removal of hydraulic jacks, installation of beams for the new ground floor;



10) completion of new ground floor.

Figure 9. Steps for isolators installation in Building in via Di Vincenzo 23 (Case Study 2).

The seismic isolation system includes 35 elastomeric isolators, type SI-S 600/200 and 35 free sliding bearings, type VM 200/700/700 (Fig. 10). Both isolator types have maximum displacement capacity of +/- 350 mm. The displacement capacity required is much higher than in Case Study 1, mainly because the soil type is worse. The fundamental period changes from the original value of 1.05s to 3.2 s. The seismic risk class [4] changes from F for the original building to B for the seismically isolated building. And the C/D ratio changes from 0.03 to 0.75.

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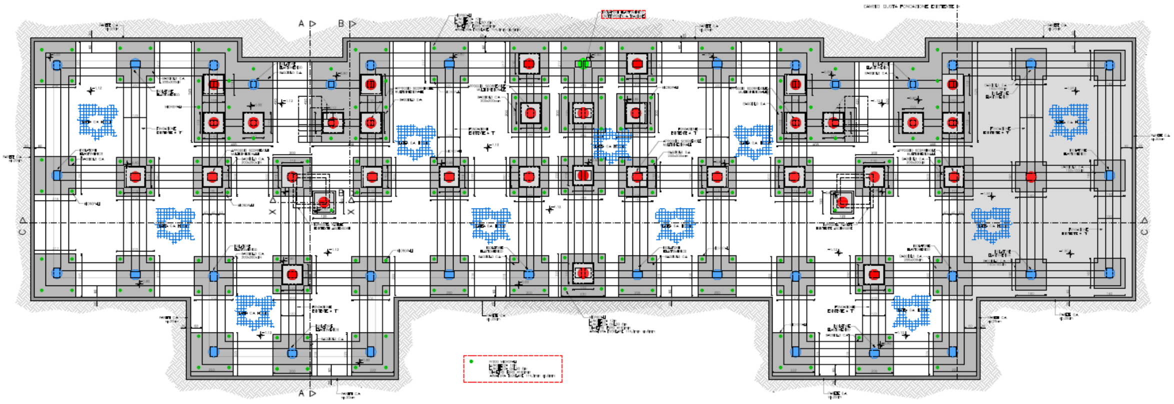

Figure 10. Plan of the isolation system for the building in via Di Vincenzo 23.
Elastomeric isolators are in blu, free sliding pot bearings in red.

5. Case study 3: building in via Di Vincenzo 23 A

The building complex includes two units, with r.c. framed structure, separated by a joint (Fig. 11). The foundation is on piles connected by beams in both directions. Each built unit has a plan of 29.55m x 13.3m, and an height of 16.5 m. In this case the existing joint is not large enough to allow displacement under earthquake, not just for isolated buildings, but for fixed base buildings as well.

Figure 11. View of the building complex in via Di Vincenzo 23 A (at the right, image from Google Maps).

The solutions selected for the insertion of the isolators in previous two case studies were not feasible in this building, due to its geometry, in particular the height of the basement used as garage. Thus, a third solution has been studied, i.e. the insertion of the isolators immediately below the existing foundation beams, on top of the piles (Fig. 12 and Fig. 13). This solution made necessary an excavation below the existing foundation for a depth of about 3.3 m (of course after the construction of a new retaining wall), and the construction of a new foundation slab properly connected to the existing piles. Around each pile, two r.c. plinths are built, above and below the volume where the isolator shall be installed. Then, hydraulic jacks are inserted between said two new plinths, and loaded, so that the vertical load is transmitted through the jacks to the bottom plinth, and the top portion of pile can be cutted. The isolators are then inserted and loaded through non-returnable flat jacks, as in previous two cases. The installation is then completed with proper grouting of the isolators and with the construction of a new floor above the isolators, stiff enough in its plan to guarantee a rigid body motion of the isolated buildings. Said new floor connect the two building units, as the new foundation slab does; the existing joint between the two built units keep its function as thermal joint only, while under earthquake the isolated building behave as one unit. Fig. 14 shows all the steps described above for the installation of the isolators.

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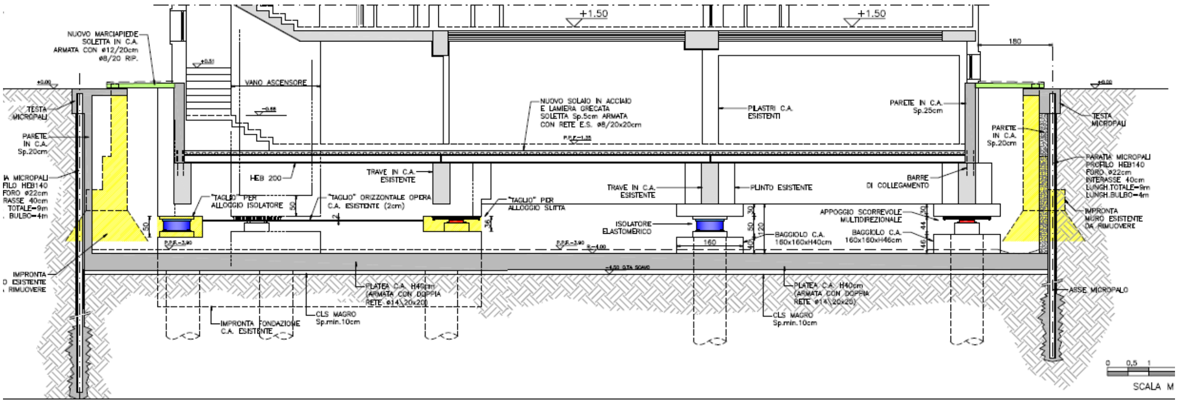


Figure 12. Cross section of the building in via Di Vincenzo 23 A at the basement/foundation level.

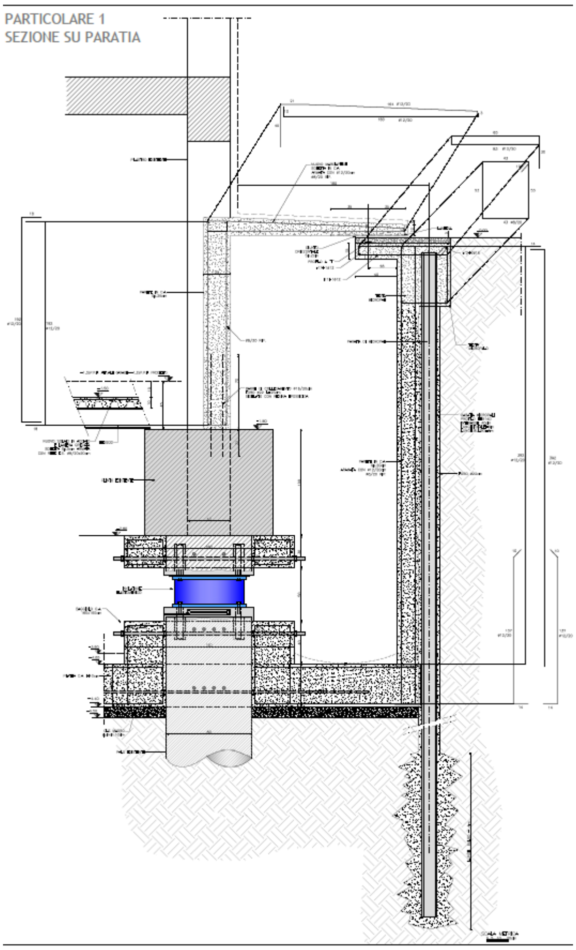
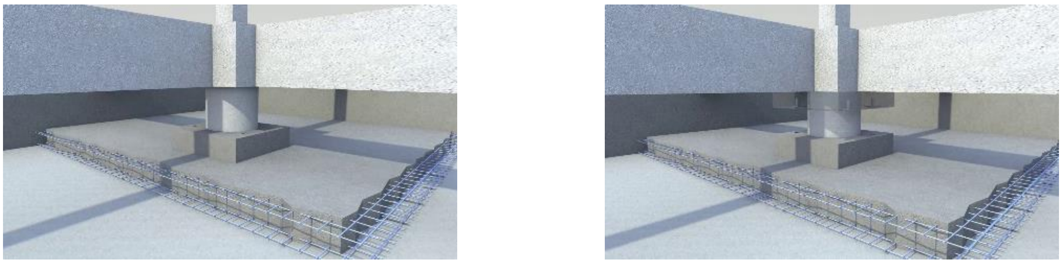


Figure 13. Cross section of the building in via Di Vincenzo 23 A:
detail of the perimetral retaining wall and of an isolator installed on the perimeter of the building.

The seismic isolation system includes 23 elastomeric isolators, type SI-N 650/162, and 24 free sliding bearings, type VM 350/700/700 (Fig. 15). The maximum displacement capacity is ±350 mm. Thanks to seismic isolation, the fundamental period increases from the original value of 0.85s to 2.57s. The consequent reduction of earthquake input energy transmitted to the superstructure allows that the seismic risk class [4] changes from E for the original building to B for the seismically isolated building. The C/D ratio changes from 0.16 to 0.71.

1) excavation below the existing foundation beams;

2) placing reinforcement for the new structure (plinths and foundation slab);



3) the new foundation slab and the bottom plinth;

4) the top plinth including dowels for the mechanical connection of the isolator;

5) placing of hydraulic jacks and displacement transducers;

6) cutting the top of the pile with diamond wire;

7) the isolator during installation: non-returnable flat jack has been already injected, while bottom anchorage grouting is not yet carried out.

Figure 14. Steps for isolators installation in Building in via Di Vincenzo 23 A.

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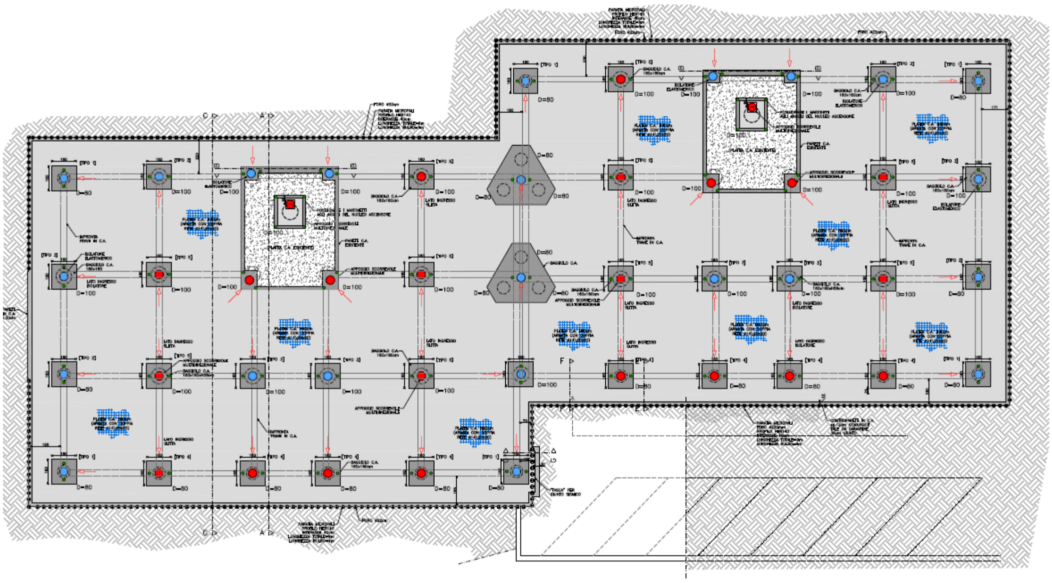

Figure 15. Isolation system of the building in via Di Vincenzo 23 A:
Elastomeric isolators are in blu, free sliding pot bearings in red.

5. Conclusions

The three case studies described above show the feasibility and advantages of seismic isolation of buildings in use. The apartments use was never interrupted during the works, only the garages were temporarily not available. The different positions of the seismic isolation layer where selected on the basis of the peculiar geometry of each building. The solution used in case study 1 is the simplest and the cheapest. However, in all the 3 cases the costs were fully within the limits of conventional retrofit works, defined by the Italian state within the tax reduction law used for such works.

The improvement in seismic behaviour is impressive. The original C/D ratio was originally not higher than 0.16, and after seismic isolation becomes higher than 0.7, and this goal was reached without any intervention in the superstructure. The seismic isolation system is designed for C/D ratio equal to 1, and for an earthquake stronger than the design earthquake for the building, corresponding to the Collapse Limit State, according to the Italian Seismic Standard.

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References

[1] Clemente P. (2023): Applications and recent studies on seismic isolation in Italy. In: Cimellaro G.P. (ed) *Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures. WCSI 2022*. Lecture Notes in Civil Engineering, Vol. 309, 3-16. Springer, Cham. Invited lecture, https://doi.org/10.1007/978-3-031-21187-4_1

[2] Bayley, J., Allen, E., (1989): Seismic isolation retrofitting of the Salt Lake City and County building, *Post-SMIRT 8 Seminar*, paper 14.

[3] Mezzi, M., Petrella, P. (2015): Base isolation in seismic retrofitting of buildings damaged by 2009 L'Aquila earthquake, *14th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures*, San Diego, USA.

[4] Cosenza, E., Del Vecchio, C., Di Ludovico, M. et al. (2018): The Italian guidelines for seismic risk classification of constructions: technical principles and validation. *Bull Earthquake Eng*, **16**, 5905–5935. doi: https://doi.org/10.1007/s10518-018-0431-8